

# COMPENDIUM OF CLAIMS AND PROOFS

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Date: August 13, 2014.

## 1. THE STAR PRODUCT

**Definition 1.1** (The Star Operator). (*October 17, 2010, January 17, 2013*)

- **On Two Surfaces**

Let  $f(x, y)$  and  $g(x, y)$  be surfaces so that  $f, g: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$ . The star operator  $\star: [0, 1]^2 \times [0, 1]^2 \rightarrow [0, 1]^2$  takes two surfaces and creates another in the following way:

$$(f(x, y), g(x, y)) \rightsquigarrow (f(1 - y, z), g(x, y)) \rightsquigarrow h(x, z) \rightsquigarrow h(x, y)$$

with the central transformation being defined by  $\diamond: [0, 1]^2 \times [0, 1]^2 \rightarrow [0, 1]^2$

$$f(1 - y, z) \diamond g(x, y) = \int_0^1 f(1 - y, z)g(x, y) dy = h(x, z)$$

and the last transformation that takes  $h(x, z) \rightsquigarrow h(x, y)$  we will call  $j: [0, 1]^2 \rightarrow [0, 1]^2$ . Thus

$$f(x, y) \star g(x, y) = j(f(1 - y, z) \diamond g(x, y)) = j\left(\int_0^1 f(1 - y, z)g(x, y) dy\right)$$

In the special case where  $f(x, 0)$ , we have

$$f(1 - y, 0) \diamond g(x, y) = \int_0^1 f(1 - y, 0)g(x, y) dy = h(x, 0)$$

motivating the following simplification:

- **On a Function and a Surface**

Let  $f(x)$  be a function  $f: [0, 1] \rightarrow \mathbb{R}$ , and  $g(x, y)$  a function such that  $g: [0, 1]^2 \rightarrow \mathbb{R}$ . The star operator  $\star: [0, 1] \times [0, 1]^2 \rightarrow [0, 1]$  takes the function and the surface and creates another function in the following way:

$$(f(x), g(x, y)) \rightsquigarrow (f(1 - y), g(x, y)) \rightsquigarrow h(x)$$

with the last transformation being defined by  $\diamond: [0, 1] \times [0, 1]^2 \rightarrow [0, 1]$

$$f(1 - y) \diamond g(x, y) = \int_0^1 f(1 - y)g(x, y) dy = h(x)$$

Thus we have

$$f(x) \star g(x, y) = f(1 - y) \diamond g(x, y) = \int_0^1 f(1 - y)g(x, y) dy$$

### 1.1. Properties of the Diamond Operator.

#### 1.1.1. Linearity.

**Claim 1.1.** (*January 29, 2013*) The diamond operator is a linear operator.

**Proof** Linearity follows from the integral operator properties. Thus we have:

- **Surface diamond Surface**

Letting  $f, g, h: [0, 1]^2 \rightarrow \mathbb{R}$ , and  $c$  be a constant,

$$\begin{aligned} (c \cdot f) \diamond g &= \int_0^1 (c \cdot f(x, y)) g(x, y) dy \\ &= c \int_0^1 f(x, y) g(x, y) dy \\ &= c \cdot (f \diamond g) \end{aligned}$$

$$\begin{aligned} f \diamond (c \cdot g) &= \int_0^1 f(x, y) (c \cdot g(x, y)) dy \\ &= c \int_0^1 f(x, y) g(x, y) dy \\ &= c \cdot (f \diamond g) \end{aligned}$$

and

$$\begin{aligned}
 (f + g) \diamond h &= \int_0^1 (f(x, y) + g(x, y)) h(x, y) dy \\
 &= \int_0^1 f(x, y) h(x, y) dy + \int_0^1 g(x, y) h(x, y) dy \\
 &= f \diamond h + g \diamond h \\
 f \diamond (g + h) &= \int_0^1 f(x, y) (g(x, y) + h(x, y)) dy \\
 &= \int_0^1 f(x, y) g(x, y) dy + \int_0^1 f(x, y) h(x, y) dy \\
 &= f \diamond g + f \diamond h
 \end{aligned}$$

• **Function diamond Surface**

Letting  $d, e: [0, 1] \rightarrow \mathbb{R}$  and  $f, g: [0, 1]^2 \rightarrow \mathbb{R}$ , and  $c$  be a constant,

$$\begin{aligned}
 (c \cdot d) \diamond f &= \int_0^1 (c \cdot d(x)) f(x, y) dy \\
 &= c \int_0^1 d(x) f(x, y) dy \\
 &= c \cdot (d \diamond f) \\
 d \diamond (c \cdot f) &= \int_0^1 d(x) (c \cdot f(x, y)) dy \\
 &= c \int_0^1 d(x) f(x, y) dy \\
 &= c \cdot (d \diamond f)
 \end{aligned}$$

and

$$\begin{aligned}
 (d + e) \diamond f &= \int_0^1 (d(x) + e(x)) f(x, y) dy \\
 &= \int_0^1 d(x) f(x, y) dy + \int_0^1 e(x) f(x, y) dy \\
 &= d \diamond f + e \diamond f \\
 d \diamond (f + g) &= \int_0^1 d(x) (f(x, y) + g(x, y)) dy \\
 &= \int_0^1 d(x) f(x, y) dy + \int_0^1 d(x) g(x, y) dy \\
 &= d \diamond f + d \diamond g
 \end{aligned}$$

□

1.2. Properties of the J Transformation.

1.2.1. Linearity.

**Claim 1.2.** (January 29, 2013) The transformation  $j: [0, 1]^2 \rightarrow [0, 1]^2$  is likewise linear.

**Proof** Let  $f, g: [0, 1]^2 \rightarrow \mathbb{R}$ , and  $c$  be a constant. Then:

$$\begin{aligned}
 j(c \cdot f(x, z)) &= c \cdot f(x, y) \\
 &= c \cdot j(f(x, z))
 \end{aligned}$$

Also:

$$\begin{aligned}
 j(f(x, z) + g(x, z)) &= f(x, y) + g(x, y) \\
 &= j(f(x, z)) + j(g(x, z))
 \end{aligned}$$

□

1.2.2. *Other Properties.*

**Claim 1.3.** (*January 17, 2013*) Take the transformation  $j: [0, 1]^2 \rightarrow [0, 1]^2$  that carries  $h(x, z) \rightsquigarrow h(x, y)$ . Then:

$$\int_a^b j(h(x, z)) dx = j \left( \int_a^b h(x, z) dx \right)$$

**Proof**

$$\int_a^b j(h(x, z)) dx = \int_a^b h(x, y) dx = H(0, y)$$

On the other hand

$$j \left( \int_a^b h(x, z) dx \right) = j(H(0, z)) = H(0, y)$$

□

1.3. **Properties of the Star Operator.**1.3.1. *Linearity.*

**Corollary 1.4** (Scaling of the Star Product). (*January 30, 2013*)

Let  $d(x)$  be a function  $d: [0, 1] \rightarrow \mathbb{R}$ , and  $f(x, y)$  and  $g(x, y)$  be functions  $f, g: [0, 1]^2 \rightarrow \mathbb{R}$ ,  $c$  is a constant. Then:

- **Surface star Surface**

$$(c \cdot f) \star g = c \cdot (f \star g)$$

and

$$f \star (c \cdot g) = c \cdot (f \star g)$$

- **Function star Surface**

$$(c \cdot d) \star f = c \cdot (d \star f)$$

and

$$d \star (c \cdot f) = c \cdot (d \star f)$$

**Proof** This is a consequence of **Claim 1.1** and **Claim 1.2**.

- **Surface star Surface**

$$\begin{aligned} (c \cdot f) \star g &= j((c \cdot f(1 - y, z)) \diamond g(x, y)) \\ &= c \cdot j(f(1 - y, z) \diamond g(x, y)) \\ &= c \cdot (f \star g) \end{aligned}$$

and

$$\begin{aligned} f \star (c \cdot g) &= j(f(1 - y, z) \diamond (c \cdot g(x, y))) \\ &= c \cdot j(f(1 - y, z) \diamond g(x, y)) \\ &= c \cdot (f \star g) \end{aligned}$$

- **Function star Surface**

$$\begin{aligned} (c \cdot d) \star f &= j((c \cdot d(1 - y)) \diamond f(x, y)) \\ &= c \cdot j(d(1 - y) \diamond f(x, y)) \\ &= c \cdot (d \star f) \end{aligned}$$

and

$$\begin{aligned} d \star (c \cdot f) &= j(d(1 - y) \diamond (c \cdot f(x, y))) \\ &= c \cdot j(d(1 - y) \diamond f(x, y)) \\ &= c \cdot (d \star f) \end{aligned}$$

□

**Corollary 1.5** (Distributive Property of the Star Product). (*January 27, 2013*)

Let  $d(x), e(x)$  be a functions  $d, e: [0, 1] \rightarrow \mathbb{R}$  and  $f(x, y), g(x, y)$  and  $h(x, y)$  be functions  $f, g, h: [0, 1]^2 \rightarrow \mathbb{R}$ ,  $c$  is a constant. Then:

- **Surface star Surface**

$$(f + g) \star h = f \star h + g \star h$$

and

$$f \star (g + h) = f \star g + f \star h$$

- **Function star Surface**

$$(d + e) \star f = d \star f + e \star f$$

and

$$d \star (f + g) = d \star f + d \star g$$

**Proof** Again this is a consequence of **Claim 1.1** and **Claim 1.2**.

- **Surface star Surface**

We have:

$$\begin{aligned} (f + g) \star h &= j((f(1 - y, z) + g(1 - y, z)) \diamond h(x, y)) \\ &= j(f(1 - y, z) \diamond h(x, y) + g(1 - y, z) \diamond h(x, y)) \\ &= j(f(1 - y, z) \diamond h(x, y)) + j(g(1 - y, z) \diamond h(x, y)) \\ &= f \star h + g \star h \end{aligned}$$

The second to last line is again a consequence of **Claim 1.2**.

The second part is:

$$\begin{aligned} f \star (g + h) &= j(f(1 - y, z) \diamond (g(x, y) + h(x, y))) \\ &= j(f(1 - y, z) \diamond g(x, y) + f(1 - y, z) \diamond h(x, y)) \\ &= j(f(1 - y, z) \diamond g(x, y)) + j(f(1 - y, z) \diamond h(x, y)) \\ &= f \star g + f \star h \end{aligned}$$

where the second to last line is justified by **Claim 1.2**.

- **Function star Surface**

Rewriting the first part,

$$\begin{aligned} (d + e) \star f &= (d(1 - y) + e(1 - y)) \diamond f(x, y) \\ &= d(1 - y) \diamond f(x, y) + e(1 - y) \diamond f(x, y) \\ &= d \star f + e \star f \end{aligned}$$

follows directly from the linear properties of the diamond operator **Claim 1.1**.

Next, in the second part,

$$\begin{aligned} d \star (f + g) &= d(1 - y) \diamond (f(x, y) + g(x, y)) \\ &= d(1 - y) \diamond f(x, y) + d(1 - y) \diamond g(x, y) \\ &= d \star f + d \star g \end{aligned}$$

again by **Claim 1.1**. □

### 1.3.2. Other Properties.

**Claim 1.6** (Zero-property). (*March 31, 2013*) Let  $f$  be a surface, with  $f: [0, 1]^2 \rightarrow \mathbb{R}$ . We have that

$$0 \star f = 0$$

The statement

$$f \star 0 = 0$$

is also true if  $f: [0, 1] \rightarrow \mathbb{R}$ ,  $f$  is a function.

**Proof** First,

$$\begin{aligned} 0 \star f &= \int_0^1 0 \cdot f(x, y) dy \\ &= \int_0^1 0 dy \\ &= 0 \end{aligned}$$

Next, with  $f: [0, 1]^2 \rightarrow \mathbb{R}$ ,

$$\begin{aligned} f \star 0 &= \int_0^1 f(1-y, z) \cdot 0 \, dy \\ &= \int_0^1 0 \, dy \\ &= 0 \end{aligned}$$

and we can see that if  $f: [0, 1] \rightarrow \mathbb{R}$  we get

$$\begin{aligned} f \star 0 &= \int_0^1 f(1-y) \cdot 0 \, dy \\ &= \int_0^1 0 \, dy \\ &= 0 \end{aligned}$$

□

**Claim 1.7** (Non-commutativity). *(October 17, 2010) The star product is non-commutative.*

**Proof by Counterexample** The claim only makes sense from the viewpoint of surfaces.

- *On Surfaces*

Let  $f, g: [0, 1]^2 \rightarrow \mathbb{R}$ .

We want to show that  $f(x, y) \star g(x, y) \neq g(x, y) \star f(x, y)$ . Choose  $f(x, y) = x$  and  $g(x, y) = y$  without loss of generality. Then:

$$f(x, y) \star g(x, y) = f(x) \star g(x, y) = \int_0^1 f(1-y) \cdot g(x, y) \, dy = \int_0^1 (1-y) \cdot y \, dy = \int_0^1 (y - y^2) \, dy = \frac{1}{6}$$

and

$$g(x, y) \star f(x, y) = j \left( \int_0^1 g(1-y, z) \cdot f(x, y) \, dy \right) = j \left( \int_0^1 (z \cdot x) \, dy \right) = j(z \cdot x) = y \cdot x$$

are non-equal.

□

**Claim 1.8** (Associativity). *(October 17, 2010) The star product is associative.*

**Proof** Again the claim only makes sense for the star operator on surfaces.

- *On Surfaces*

Let  $f, g, h: [0, 1]^2 \rightarrow \mathbb{R}$ .

We want to show that  $[f(x, y) \star g(x, y)] \star h(x, y) = f(x, y) \star [g(x, y) \star h(x, y)]$ .

The LHS is:

$$\begin{aligned} [f(x, y) \star g(x, y)] \star h(x, y) &= j \left( \int_0^1 f(1-y, z) g(x, y) \, dy \right) \star h(x, y) \\ &= j \left( \int_0^1 \int_0^1 f(1-z, w) g(1-y, z) \, dz h(x, y) \, dy \right) \\ &= j \left( \int_0^1 \int_0^1 f(1-z, w) g(1-y, z) h(x, y) \, dz \, dy \right) \end{aligned}$$

The RHS is:

$$\begin{aligned} f(x, y) \star [g(x, y) \star h(x, y)] &= f(x, y) \star j \left( \int_0^1 g(1-y, z) h(x, y) \, dy \right) \\ &= j \left( \int_0^1 f(1-z, w) \int_0^1 g(1-y, z) h(x, y) \, dy \, dz \right) \\ &= j \left( \int_0^1 \int_0^1 f(1-z, w) g(1-y, z) h(x, y) \, dy \, dz \right) \end{aligned}$$

We immediately see the equivalence using the Fubini Theorem to exchange the order of integration.

□

#### 1.4. Mechanics of Powering.

**Claim 1.9** (Powering Symmetry). (*December 30, 2012*) Take  $f: [0, 1]^2 \rightarrow \mathbb{R}$ . Let the  $n$ th power of  $f(x, y)$ ,  $f_n(x, y)$  be denoted shorthand by  $F^n$  (for Pasquali patches, we use the notation  $P^n$  and  $p_n(x, y)$  interchangeably). Then for  $m, n \geq 1$ ,  $F^n \star F^m = F^m \star F^n$ .

**Proof by Induction** By definition of powering,

$$F^1 \star F^m = F^1 \star \underbrace{(F^1 \star \dots \star F^1)}_{m \text{ times}}$$

Then, by **Claim 1.8 Associativity of the Star Product**, this is equivalent to

$$\underbrace{(F^1 \star \dots \star F^1)}_{m \text{ times}} \star F^1 = F^m \star F^1$$

Next assume that, for fixed  $k, m \geq 1$ ,  $F^k \star F^m = F^m \star F^k$ .

Then  $F^{k+1} \star F^m = (F^1 \star F^k) \star F^m$ , where this bit we take as the definition of powering, and then, by **Claim 1.8** again,  $F^1 \star (F^k \star F^m)$ , which then by our inductive hypothesis equals  $F^1 \star (F^m \star F^k)$  and this is  $(F^m \star F^k) \star F^1$  by the inductive basis. Again, **Claim 1.8** gives  $F^m \star (F^k \star F^1)$  and lastly  $F^m \star F^{1+k}$  by definition of powering. Axiomatic commutativity of the positive integers gives  $F^m \star F^{k+1}$  and we are done.

By symmetry of equality itself, we need only do a single proof of induction on one of the power parameters.  $\square$

**Claim 1.10.** (*December 30, 2012*) Again take  $f: [0, 1]^2 \rightarrow \mathbb{R}$ .  $F^n \star F^m = F^{m+n}$ .

**Proof by Induction** First, fix  $m \geq 1$ . By the definition of powering,  $F^1 \star F^m = F^{m+1}$ . Next, suppose it's true that  $F^k \star F^m = F^{m+k}$ . Then  $F^{k+1} \star F^m$  equals  $(F^1 \star F^k) \star F^m$  by definition of powering, and by **Claim 1.8 Associativity of the Star Product** we get  $F^1 \star (F^k \star F^m)$  or  $F^1 \star F^{m+k}$  using the inductive hypothesis. By the inductive basis, this becomes  $F^{(m+k)+1}$ , that is  $F^{m+(k+1)}$  using associativity of the positive integers, which we take as axiomatic.

Having done so, next fix  $n \geq 1$  and let  $m$  vary. We have  $F^n \star F^1 = F^1 \star F^n$  by **Claim 1.9 Powering Symmetry**. Since this part of the proof is identical to the one we just wrote, we are done.  $\square$

##### 1.4.1. Special Subcollections of Powers.

**Remark 1.1.** (*January 13, 2014*) If we accept powering of functions via the definitions of the star product, then the following will make sense. On the other hand if we view this from the standpoint of simple matrices (and replace the star product by matrix multiplication), the following claims may also make sense.

**Definition 1.2.** (*January 13, 2014*) For a countably infinite collection  $\mathbb{F} = \{F^1, F^2, \dots, F^j, \dots\}_{j \in \mathbb{Z}^+}$ , the generator is  $F^1$  since all other elements in the collection are powers of such. (As an aside, we may contemplate finite collections in the event of powering periodicity or nilpotency, but not presently).

**Claim 1.11.** (*January 13, 2014*) Take the countably infinite collections  $\mathbb{F}$  and  $\mathbb{G}$  with generators  $F^1$  and  $G^1$  respectively. If  $F^1 = G^1$ , then  $\mathbb{F} = \mathbb{G}$ .

**Proof by Induction** By hypothesis we have that  $F^1 = G^1$ , and let us assume that  $F^k = G^k$ . Then:

$$F^{k+1} = F^1 \star F^k = G^1 \star G^k = G^{k+1}$$

Thus we have shown that  $\mathbb{F} \subset \mathbb{G}$  and  $\mathbb{G} \subset \mathbb{F}$  and so naturally we conclude  $\mathbb{F} = \mathbb{G}$ .  $\square$

**Claim 1.12.** (*January 13, 2014*) Take the countably infinite collections  $\mathbb{F}$  and  $\mathbb{G}$  with generators  $F^1$  and  $G^1$  respectively. If  $F^1 = G^n$  for some  $n \in \mathbb{Z}^+$ , then  $\mathbb{F} \subset \mathbb{G}$ .

**Proof by Induction** By hypothesis  $F^1 = G^n$  for some positive integer  $n$ . Also,

$$F^2 = F^1 \star F^1 = G^n \star G^n = G^{2n}$$

using **Claim 1.10**. Next suppose that  $F^k = G^{kn}$ . Then:

$$F^{k+1} = F^1 \star F^k = G^n \star G^{kn} = G^{n+kn} = G^{(k+1)n}$$

Thus  $\mathbb{F} \subset \mathbb{G}$  since all elements of the collection  $\mathbb{F}$  are contained in  $\mathbb{G}$ .  $\square$

**Definition 1.3** (Subsequent Power Subset at  $n$ ). (*January 13, 2014*) For a countably infinite collection  $\mathbb{F} = \{F^1, F^2, \dots, F^j, \dots\}_{j \in \mathbb{Z}^+}$ , we call the subset  $\mathbb{F}_n \subset \mathbb{F}$  the subsequent power subset at  $n$ , and it is composed of all those powers greater than or equal to  $n \in \mathbb{Z}^+$ .

**Claim 1.13.** (*January 13, 2014*) Take the countably infinite collections  $\mathbb{F}$  and  $\mathbb{G}$  with generators  $F^1$  and  $G^1$  respectively. If  $F^m = G^n$  for some  $m, n \in \mathbb{Z}^+$  and  $m < n$  (since we haven't defined roots it must also be true that  $\frac{n}{m} \in \mathbb{Z}^+$ ), then  $\mathbb{F}_m \subset \mathbb{G}_n \subset \mathbb{G}$ . (At this point we don't really care about containment of powers less than  $n$ , since we haven't established a mechanism to obtain them by unpowering or taking roots).

**Proof by Induction** By hypothesis  $F^m = G^n$ . In particular, we have the statement  $F^{m+1} = G^{n+p}$  for some integer  $p \in \mathbb{Z}^+$ . (Advancing one element in the collection  $\mathbb{F}$  starting from  $m$ , advances us  $p$  units in the collection  $\mathbb{G}$  starting from  $n$ .) Taking this statement to the logical consequence,  $F^m \star F^1 = G^n \star G^p \Rightarrow F^1 = G^p$ . (Notice that since we have not defined negative powers of functions,  $p$  is necessarily a positive integer).

Next let us assume that  $F^{m+k} = G^{n+kp}$ . Then:

$$F^{m+(k+1)} = F^{(m+k)+1} = F^{m+k} \star F^1 = G^{n+kp} \star G^p = G^{n+(k+1)p}$$

It can be seen now that  $\mathbb{F}_m \subset \mathbb{G}_n \subset \mathbb{G}$ . □

**Corollary 1.14.** (*January 13, 2014*) Take the countably infinite collections  $\mathbb{F}$  and  $\mathbb{G}$ .  $\mathbb{F}_m = \mathbb{G}_n \subset \mathbb{G}$  if and only if  $m = n$  and  $p = 1$ .

**Proof** We have:

- $\Rightarrow$  Since  $\mathbb{F}_m = \mathbb{G}_n$  there is no element of either collection that does not match one in the other collection. Thus the step between elements must be 1, and  $p = 1$ . Furthermore the elements in a collection can be put in bijective correspondence (by definition of equality of sets) with the elements in the other collection, and the indices must exactly coincide by the ordering being the usual order on the positive integers (we order by power). Thus  $m = n$ .
- $\Leftarrow$  (**Proof by Induction**) Since  $m = n$  we have that  $F^m = G^n \Rightarrow F^m = G^m$  for all  $m \in \mathbb{Z}^+$ , and also  $F^{m+1} = G^{n+p} \Rightarrow F^{m+1} = G^{m+1}$  since  $p = 1$ . So now assume that this works for the  $k$ th element  $k > m + 1$ , so that  $F^{m+k} = G^{m+k} \Rightarrow F^k = G^k$ . Then we have that:

$$F^{m+(k+1)} = F^{(m+1)+k} = F^{(m+1)} \star F^k = G^{(m+1)} \star G^k = G^{(m+1)+k} = G^{m+(k+1)}$$

and we are done. □

## 2. Pasquali Patches

### 2.1. Definitions and Constructions.

**Definition 2.1** (*Pasquali patch*). (*April 22, 2010*) Define a continuous, bounded surface  $p(x, y)$ , with  $p: [0, 1] \times [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$ , and let  $\int_0^1 p(x, y) dx = 1$  be true regardless of the value of  $y$ . In other words, integrating such surface with respect to  $x$  yields the uniform probability distribution  $u(y)$ ,  $u: [0, 1] \rightarrow \{1\}$ . We will call this a Pasquali patch.

**Construction 2.1.** (*October 10, 2010*) A way to construct a Pasquali patch is by positing

$$p(x, y) = f_1(x)g_1(y) + f_2(x) \frac{1 - g_1(y) \int_0^1 f_1(x) dx}{\int_0^1 f_2(x) dx} = f_1(x)g_1(y) + f_2(x) \frac{1 - g_1(y)F_1}{F_2}$$

for arbitrary function choices  $f_{1,2}(x)$ , and  $g_1(y)$ .

**Proof** Since for *Pasquali patches*  $\int_0^1 p(x, y) dx = 1$ , it can be seen that such construction is a *Pasquali patch* because

$$\int_0^1 \left( f_1(x)g_1(y) + f_2(x) \frac{1 - g_1(y)F_1}{F_2} \right) dx = g_1(y)F_1 + \frac{F_2}{F_2} - \frac{g_1(y)F_1F_2}{F_2} = 1$$

regardless of function choices of  $y$ . □

### 2.2. Properties of Pasquali Patches Under the Star Operator.



2.2.1. *Notable Properties.*

**Claim 2.1** (Closure of *Pasquali Patches*). (*October 12, 2010*) A *Pasquali patch star* a *Pasquali patch* yields a new *Pasquali patch*. In particular, a *Pasquali patch star itself* (*Pasquali patch powers*) will always yield another *Pasquali patch*.

**Proof** Take *Pasquali patches*  $p(x, y)$  and  $q(x, y)$ . We want to show that  $p(x, y) \star q(x, y) = r(x, y)$  is a *Pasquali patch*. Thus, we want to show that  $\int_0^1 r(x, y) dx = 1$ . In other words,

$$\int_0^1 j \left( \int_0^1 p(1-y, z) q(x, y) dy \right) dx = 1$$

By **Claim 1.3**, we can write this as

$$j \left( \int_0^1 \int_0^1 p(1-y, z) q(x, y) dy dx \right)$$

We can exchange the order of integration because of absolute convergence of the integrals (Fubini Theorem). Thus

$$j \left( \int_0^1 p(1-y, z) \int_0^1 q(x, y) dx dy \right)$$

yields

$$j \left( \int_0^1 p(1-y, z) u(y) dy \right) = j \left( \int_0^1 p(1-y, z) dy \right)$$

This final integral evaluates to  $j(u(z)) = u(y) = 1$  for any choice of  $y$ . Thus  $\int_0^1 r(x, y) dx = 1$ . □

**Example 2.1.** (*October 12, 2010*) Take the *Pasquali patch*  $p(x, y) = x^2 y^3 + x \left( 2 - \frac{2y^3}{3} \right)$ . It is evident it is a *Pasquali patch* because

$$\int_0^1 \left[ x^2 y^3 + x \left( 2 - \frac{2y^3}{3} \right) \right] dx = \left[ \frac{x^3}{3} y^3 + \frac{x^2}{2} \left( 2 - \frac{2y^3}{3} \right) \right] \Big|_0^1 = 1$$

We can calculate

$$p(1-y, z) = z^3 y^2 - \frac{4z^3 y}{3} + \frac{z^3}{3} - 2y + 2$$

so that the second “power” of the *Pasquali patch* is

$$p_2(x, y) = j \left( \int_0^1 p(1-y, z) p(x, y) dy \right) = j \left( \frac{29x}{15} + \frac{z^3 x}{90} + \frac{x^2}{10} - \frac{z^3 x^2}{60} \right)$$

and the final transformation  $j$  of the star operator gives

$$p_2(x, y) = \frac{29x}{15} + \frac{y^3 x}{90} + \frac{x^2}{10} - \frac{y^3 x^2}{60}$$

One easily checks  $p_2(x, y)$  is indeed a *Pasquali patch* by performing the integral  $\int_0^1 p_2(x, y) dx$  and ascertaining its equality to 1. The third *Pasquali patch power* is

$$p_3(x, y) = \frac{1741x}{900} - \frac{y^3 x}{5400} + \frac{59x^2}{600} + \frac{y^3 x^2}{3600}$$

**Example 2.2.** (*October 15, 2010, October 17, 2010*) The *Pasquali patch*

$$p(x, y) = 1 - \cos(2\pi x) \cos(2\pi y)$$

has powers:

$$\begin{aligned}
p(x, y) &= 1 - \cos(2\pi x) \cos(2\pi y) \\
p_2(x, y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{2} \\
p_3(x, y) &= 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{4} \\
p_4(x, y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{8} \\
p_5(x, y) &= 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{16} \\
p_6(x, y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{32} \\
&\vdots \\
p_n(x, y) &= 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(n-1)}}
\end{aligned}$$

**Proof by Induction** We show that, by the inductive basis,  $p(x, y) = 1 - \cos(2\pi x) \cos(2\pi y)$  must equal

$$p_1(x, y) = 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(0)}}$$

which a quick check shows is indeed the case.

Next, by the inductive step, we take as true that:

$$p_k(x, y) = 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(k-1)}}$$

Then,

$$\begin{aligned}
p_{k+1}(x, y) &= j \left( \int_0^1 p_1(1-y, z) \cdot p_k(x, y) dy \right) \\
&= j \left( \int_0^1 (1 - \cos(2\pi(1-y)) \cos(2\pi z)) \cdot \left( 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{k-1}} \right) dy \right)
\end{aligned}$$

The product of 1 with itself is 1, and such will integrate to 1 in the unit interval. So we save it. The integrals  $\int_0^1 \cos(2\pi y) dy$  and  $\int_0^1 \cos(2\pi - 2\pi y) dy$  both evaluate to zero, so we are left only with the task of evaluating the crossterm:

$$\begin{aligned}
\int_0^1 \cos(2\pi(1-y)) \cos(2\pi z) \cdot \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{k-1}} dy &= \frac{\cos(2\pi z) \cos(2\pi x)}{(-2)^{k-1}} \int_0^1 \cos(2\pi - 2\pi y) \cos(2\pi y) dy \\
&= \frac{\cos(2\pi z) \cos(2\pi x)}{(-2)^{k-1}} \int_0^1 \cos^2(2\pi y) dy \\
&= \frac{\cos(2\pi z) \cos(2\pi x)}{(-2)^{k-1}} \cdot \frac{1}{2} \\
&= -\frac{\cos(2\pi z) \cos(2\pi x)}{(-2)^k}
\end{aligned}$$

Let's not forget the 1 we had saved, so:

$$p_{k+1}(x, y) = j \left( 1 - \frac{\cos(2\pi x) \cos(2\pi z)}{(-2)^k} \right) = 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^k}$$

as we wanted to show.  $\square$

**Remark 2.1.** (*April 22, 2010*) **Probabilistic Interpretation.** In direct analogy to the Chapman-Kolmogorov equation, transition from state  $y \in [0, 1]$  to  $x \in [0, 1]$  in  $n + m$  steps can be achieved by first transitioning to an intermediate state  $x^\bullet$  in  $n$  steps and then jumping from there to  $x$  in  $m$  more steps. Particularly, all states are achievable from a starter state since for Pasquali patch  $p(x, y)$  there are only a finite number of zeroes in the domain because the surface is well-behaved.

2.2.2. Other Properties.

**Claim 2.2** (Non-commutativity of *Pasquali Patches* Under the Star Product). (*October 17, 2010*) We know in general the star product is non-commutative (**Claim 1.7**), but we don't know that *Pasquali patches* as a subset of surfaces with domain on  $[0, 1] \times [0, 1]$  ("Pasquali patchixes", due to their resembling matrixes in that they transform functions to other functions, as matrixes transform vectors to other vectors) don't commute.

**Proof by Counterexample** Suppose the *Pasquali patches*  $p(x, y) = x + \frac{1}{2}$  and  $q(x, y) = 1 + xy - \frac{y}{2}$ . Then

$$\begin{aligned} p(x, y) \star q(x, y) &= p(x) \star q(x, y) = \int_0^1 p(1-y) \cdot q(x, y) dy \\ &= \int_0^1 \left(\frac{3}{2} - y\right) \cdot \left(1 + xy - \frac{y}{2}\right) dy \\ &= \frac{5x}{12} + \frac{19}{24} \end{aligned}$$

where

$$\begin{aligned} q(x, y) \star p(x, y) &= j \left( \int_0^1 q(1-y, z) \cdot p(x, y) dy \right) \\ &= j \left( \int_0^1 q(1-y, z) \cdot p(x) dy \right) \\ &= j \left( p(x) \int_0^1 q(1-y, z) dy \right) \\ &= j (p(x) \cdot u(z)) = p(x) \\ &= x + \frac{1}{2} \end{aligned}$$

□

**Corollary 2.3** (Associativity of *Pasquali Patches* Under the Star Product). (*October 17, 2010, December 3, 2012*) *Pasquali patches* inherit associativity.

**Proof** *Pasquali patches* inherit associativity from the star product through **Claim 1.8 Associativity of the Star Product**. □

2.3. Limiting Surface.

**Definition 2.2.** The limiting, steady-state, or stationary surface is a surface obtained by taking the limit as  $n$  approaches infinity of *Pasquali patch powers*  $\lim_{n \rightarrow \infty} p_n(x, y)$ , provided it exists, and we call it  $p_\infty(x, y)$ .

**Lemma 2.4.** (*October 17, 2010*) The stationary surface of

$$p(x, y) = 1 - \cos(2\pi x) \cos(2\pi y)$$

is  $p_\infty(x, y) = 1$ .

**Proof** Since the *Pasquali patch* power collection of  $p(x, y) = 1 - \cos(2\pi x) \cos(2\pi y)$  can be described by

$$p_n(x, y) = 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(n-1)}}$$

due to **Example 2.2** we need only take the limit as  $n$  approaches infinity of this formula:

$$\lim_{n \rightarrow \infty} p_n(x, y) = \lim_{n \rightarrow \infty} \left( 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(n-1)}} \right) = 1$$

In this particular case, notice that  $p_\infty(x, y) = 1$  is also a *Pasquali patch* because

$$\int_0^1 p_\infty(x, y) dx = 1$$

□

**Lemma 2.5.** (*December 3, 2012*) If the sequence  $p_n(x, y)$  of *Pasquali patch powers* converge uniformly to  $p_\infty(x, y)$ , then  $p_\infty(x, y)$  is a *Pasquali patch*.

**Proof** We want to show that  $\int_0^1 p_\infty(x, y) dx = 1$ . First,

$$\int_0^1 p_\infty(x, y) dx = \int_0^1 \lim_{n \rightarrow \infty} p_n(x, y) dx$$

By uniform convergence of the sequence of *Pasquali patches*, we can exchange the order of the limit to obtain

$$\lim_{n \rightarrow \infty} \int_0^1 p_n(x, y) dx$$

Now for any  $n$ ,  $p_n(x, y)$  is a Pasquali patch, and therefore the integral is equal to 1 in every case (for any choice of  $n$ ). Lastly,

$$\lim_{n \rightarrow \infty} \{1\}_n = 1$$

and we have arrived at what we wanted to show.  $\square$

**Claim 2.6.** (*December 3, 2012*) Pasquali patches that are functions of  $y$  (possibly  $x$ ) explicitly generate by self-powering a countably infinite collection of Pasquali patches that are functions of  $y$  (possibly  $x$ ) explicitly.

**Proof by Induction** Let  $p(x, y)$  be a *Pasquali patch* that is a function of  $y$  (possibly  $x$ ) explicitly. Thus the basis is true by hypothesis. By the inductive step, let  $p_k(x, y)$ ,  $k \in \mathbb{Z}^+$  be an explicit function of  $y$  (possibly  $x$ ). Then:

$$p_{k+1}(x, y) = p_k(x, y) \star p(x, y) = j \left( \int_0^1 p_k(1-y, z) p(x, y) dy \right)$$

is an explicit function of  $y$  (possibly  $x$ ) since  $p_k(x, y)$  was an explicit function of  $y$  (possibly  $x$ ), and the  $y$  was saved by the transformation to  $z$  in  $p_k(1-y, z)$ , so that the integral did not aggregate it. Then, the transformation  $j$  takes  $z \rightsquigarrow y$  makes  $p_{k+1}(x, y)$  an explicit function of  $y$  (possibly  $x$ ). The result is a countable collection of explicit functions of  $y$  (possibly  $x$ ) via self-powering, because  $k \in \mathbb{Z}^+$ .  $\square$

**Claim 2.7.** (*October 17, 2010*) A Pasquali patch star a Pasquali patch that is solely a function of  $x$  returns the second Pasquali patch.

**Proof** Suppose the *Pasquali patches*  $q(x, y)$  and  $p(x, y) = p(x)$ . Then:

$$\begin{aligned} q(x, y) \star p(x, y) &= j \left( \int_0^1 q(1-y, z) \cdot p(x) dy \right) \\ &= j \left( p(x) \int_0^1 q(1-y, z) dy \right) \\ &= j(p(x) \cdot u(z)) = p(x) \end{aligned}$$

$\square$

**Claim 2.8.** (*December 3, 2012*) Pasquali patches that are functions of  $x$  alone (explicitly or otherwise) generate Pasquali patches that are the same as the original Pasquali patch via self-powering.

**Proof by Induction**  $p(x) = p(x)$  by the identity of equality.  $p_2(x) = p(x) \star p(x) = p(x)$  by **Claim 2.7**. This establishes the induction basis. Next, suppose  $p_k(x) = p(x)$ . Then  $p_{k+1}(x) = p_k(x) \star p(x) = p(x) \star p(x) = p(x)$ , and we are done.  $\square$

**Claim 2.9.** (*December 3, 2012*) If the limiting surface  $p_\infty(x, y)$  exists, it is NOT an explicit function of  $y$ . It is either an explicit function of  $x$  or constant for all  $x, y$ . We can describe it WLOG by  $p_\infty(x)$ .

**Proof** The proof consists of two cases.

- Case 1. Suppose we have a generator *Pasquali patch*  $p(x)$  which is a function of  $x$  alone (explicitly or otherwise). Then, by **Claim 2.8**,  $\forall n \in \mathbb{Z}^+$ ,  $p_n(x) = p(x)$ . Taking the limit as  $n$  approaches infinity, we obtain  $\lim_{n \rightarrow \infty} p_n(x) = \lim_{n \rightarrow \infty} p(x)$ , or  $p_\infty(x) = p(x)$ . This limiting surface is therefore also a *Pasquali patch*.
- Case 2. In the space of uniformly convergent surfaces generated by *Pasquali patch* self-powers, the limiting surface will exist and will be a *Pasquali patch* itself by **Lemma 2.5**. Now suppose that  $p_\infty(x, y)$  is an explicit function of  $y$  (possibly  $x$ ). Then either it belongs to the collection of *Pasquali patch* powers generated by  $p(x, y)$ , or to a different collection altogether generated by *Pasquali patch* powers of, say,  $q(x, y)$ . If it belongs to the collection of *Pasquali patch* powers generated by  $p(x, y)$ , it must be equal to  $p_n(x, y)$  for some  $n$ . But such is not an accumulation surface because we can generate  $p_{n+1}(x, y)$  and onwards. It therefore must belong to a different collection, that generated by  $q(x, y)$ , and equals  $q_m(x, y)$  for some  $m$ . The problem is that such isn't an accumulation surface either, being part of a (different) sequence of *Pasquali patch* powers,

and in a “parallel” collection. We are faced with a contradiction.  $p_\infty(x, y)$  must therefore NOT be an explicit function of  $y$ : it is either explicitly or not a function of  $x$ , that is,  $p_\infty(x)$ . Recall it is also a *Pasquali patch* by **Lemma 2.5**. □

**2.4. Probability Distribution Transformations via *Pasquali Patches*.**

**Claim 2.10. (October 10, 2010)** *A well-behaved continuous probability distribution  $b: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$  with  $\int_0^1 b(x) dx = 1$ , **star** a *Pasquali patch*, yields a continuous probability distribution  $c: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$  with  $\int_0^1 c(x) dx = 1$ . In other words, a probability distribution  $b(x)$  is taken to a probability distribution  $c(x)$  via the *Pasquali patch*:  $b(x) \rightsquigarrow c(x)$ .*

**Proof 1** Let  $c(x) = b(x) \star p(x, y)$ . We seek to show that

$$\int_0^1 c(x) dx = \int_0^1 b(x) \star p(x, y) dx = 1$$

Using **Definition 1.1**,

$$\int_0^1 b(x) \star p(x, y) dx = \int_0^1 \int_0^1 b(1-y)p(x, y) dy dx$$

Absolute convergence of the integrals allows us to exchange the order of integration (Fubini Theorem). Thus:

$$\int_0^1 \int_0^1 b(1-y)p(x, y) dx dy = \int_0^1 b(1-y) \int_0^1 p(x, y) dx dy$$

The innermost integral adds up to  $u(y) = 1$  by **Definition 2.1**. Next

$$\int_0^1 b(1-y)u(y) dy = \int_0^1 b(1-y) \cdot 1 dy = 1$$

by virtue of  $b(x)$  being a probability distribution. □

**Proof 2** Via **Closure of *Pasquali Patches* (Claim 2.1)**, a continuous probability distribution  $b(x)$  can be thought of as  $b(x, y)$  and a *Pasquali patch*, thus it **star** another *Pasquali patch* will yield a new *Pasquali patch* by closure of *Pasquali patches*. □

**Example 2.3. (October 10, 2010)** *Let  $b(x) = 6x(1-x)$ . This is a  $\text{beta}(2,2)$  probability distribution and*

$$\int_0^1 (6x(1-x)) dx = \int_0^1 (6x - 6x^2) dx = (3x^2 - 2x^3)|_0^1 = 1$$

*is easily checked. Let  $p(x, y) = x + \frac{1}{2}$  be a *Pasquali patch*, with*

$$\int_0^1 \left(x + \frac{1}{2}\right) dx = \left(\frac{x^2}{2} + \frac{x}{2}\right)|_0^1 = 1$$

*for any choice of  $y$ . Then*

$$b(x) \star p(x, y) = \int_0^1 b(1-y)p(x, y) dy = \int_0^1 6(1-y)(y) \left(x + \frac{1}{2}\right) dy = x + \frac{1}{2}$$

*This probability distribution has already been shown to integrate to 1 with respect to  $x$ .*

**Corollary 2.11. (October 10, 2010)** *A continuous probability distribution  $b: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$  **star** a *Pasquali patch* that solely a function of  $x$  yields a continuous probability distribution that is of the same form as the *Pasquali patch*. In other words, a probability distribution  $b(x)$  is carried via the *Pasquali patch*  $p(x, y) = p(x)$  to  $p(x)$ :  $b(x) \rightsquigarrow p(x)$ .*

**Proof 1** Using the definition of the star operator,  $\int_0^1 b(1-y)p(x, y) dy = \int_0^1 b(1-y)p(x) dy = p(x)$ . □

**Proof 2** Via **Claim 2.7**. A continuous probability distribution can be thought of as a *Pasquali patch*, and thus **Claim 2.7** applies. □

### 2.5. Fixed Distribution Conjecture.

**Conjecture 2.1.** (*December 3, 2012*) *It is only natural to ask if there exists a (bounded, well-behaved, probability) function  $a(x)$ ,  $a: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$  that remains fixed when starred by a Pasquali patch  $p(x, y)$ . In other words, is there an  $a(x)$  so that  $a(x) \star p(x, y) = a(x)$ ?*

**Claim 2.12.** (*December 3, 2012*) *Suppose **Conjecture 2.1** is true. Then  $a(x)$  remains fixed for all Pasquali patch powers generated by  $p(x, y)$ .*

**Proof by Induction** We take as true that  $a(x) \star p(x, y) = a(x)$  by **Conjecture 2.1**. By the inductive step, we have that  $a(x) \star p_k(x, y) = a(x)$ . Then:

$$a(x) \star p_{k+1}(x, y) = a(x) \star (p_k(x, y) \star p(x, y))$$

By **Claim 1.8 Associativity of the Star Product**, this last expression we can write as:

$$(a(x) \star p_k(x, y)) \star p(x, y) = a(x) \star p(x, y) = a(x)$$

and we are done. □

**Corollary 2.13.** (*July 23, 2013*) *Consider the more general eigenvalue problem*

$$a(x) \star p(x, y) = \lambda a(x)$$

*with  $p(x, y)$  is a Pasquali patch. Take **Conjecture 2.1** is true. Then  $\lambda = 1$  is an eigenvalue of all self-powers of  $p(x, y)$ .*

**Proof** The proof follows from **Claim 2.12**, since  $a(x)$  remains exactly fixed for all *Pasquali patch* powers generated by  $p(x, y)$ , implying  $\lambda = 1$ . □

**Claim 2.14.** (*December 3, 2012*) *The only function  $b(x)$  that makes true the expression  $a(x) \star b(x) = a(x)$ ,  $a(x)$  is a probability distribution  $a: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$  with  $\int_0^1 a(x) dx = 1$  (and therefore a Pasquali patch from another viewpoint), is  $a(x)$  itself.*

**Proof 1** We resort to the definition of the star operator, and the LHS is

$$a(x) \star b(x) = \int_0^1 a(1-y)b(x) dy = b(x) \int_0^1 a(1-y) dy = b(x)$$

On the other hand, the RHS is  $a(x)$ , and  $b(x) = a(x)$ . □

**Proof 2** By **Claim 2.8**, the LHS is  $b(x)$ . The RHS is  $a(x)$  and the equality is established. □

**Corollary 2.15.** (*December 3, 2012*)  $a(x) \star a(x) = a(x)$

**Proof** By **Claim 2.14**, since the only function of  $x$  that makes the expression true is  $a(x)$ , the result follows by direct plugging-in to the original expression. □

**Corollary 2.16.** (*December 3, 2012*)  $a(x)$  is fixed for the limiting Pasquali patch probability distribution of some collection of uniformly convergent Pasquali patch self-powers of  $p(x, y)$  if and only if  $p_\infty(x) = a(x)$ .

**Proof** We have:

- $\Rightarrow$  By **Claim 2.9**, the *Pasquali patch* self-powers of  $p(x, y)$  converge to  $p_\infty(x)$ , a *Pasquali patch* (by **Lemma 2.5**) which is NOT explicitly a function of  $y$ . By hypothesis,  $a(x) \star p_\infty(x) = a(x)$ . Then by **Claim 2.7**,  $a(x) \star p_\infty(x) = p_\infty(x)$ . It follows that  $p_\infty(x) = a(x)$ .
- $\Leftarrow$  By hypothesis,  $p_\infty(x) = a(x)$ , and by **Corollary 2.15**,  $a(x) \star a(x) = a(x)$ . Plugging in the first equation with the second at the appropriate location yields the desired result, and  $a(x) \star p_\infty(x) = a(x)$ . □

**Corollary 2.17.** (*December 3, 2012*)  $a(x)$  is fixed for a collection of (uniformly convergent) self-powers of the Pasquali patch  $p(x, y)$  if and only if it is fixed for the limiting Pasquali patch (by **Lemma 2.5**)  $p_\infty(x)$ .

**Proof** We have:

- $\Rightarrow$  By hypothesis,  $a(x)$  is fixed for all (uniformly convergent)  $p_n(x, y)$ . Since they are uniformly convergent, they converge to  $p_\infty(x)$ . Now,  $a(x) \star a(x) = a(x)$  is true by **Corollary 2.15**, and  $a(x)$  is the ONLY (probability) probability distribution or *Pasquali patch* that makes the statement true by **Claim 2.14**. Also,  $p_\infty(x) \star p_\infty(x) = p_\infty(x)$  by **Lemma 2.5** ( $p_\infty(x)$  is a *Pasquali patch*) and **Claim 2.8**. It follows that  $p_\infty(x) = a(x)$  with these two pieces of information. Lastly, by **Corollary 2.16** ( $\Leftarrow$ ), we have that  $a(x) \star p_\infty(x) = a(x)$ .

⇐ **(Indirect Proof)** Suppose otherwise, that  $a(x) \star p_\infty(x) = a(x)$  and  $p_\infty(x) = a(x)$  by **Corollary 2.16**, which in turn implies of **Corollary 2.15** that

$$a(x) \star a(x) = a(x) \Rightarrow p_\infty(x) \star p_\infty(x) = p_\infty(x)$$

but  $a(x) \star p(x, y) \neq a(x)$  (for some uniformly convergent  $p(x, y)$ ). Then:

$$(a(x) \star p(x, y)) \star a(x) \neq a(x) \star a(x)$$

$$a(x) \star (p(x, y) \star a(x)) \neq a(x) \star a(x)$$

by **Claim 1.8 Associativity of the Star Product**

$$a(x) \star (a(x)) \neq a(x)$$

by **Claim 2.8** and

$$p_\infty(x) \star p_\infty(x) \neq p_\infty(x)$$

contradicts the last implication of the hypothesis. □

**Remark 2.2** (Guiding Maplet). (*December 7, 2012*)

The maplets show at a high-level the most important claims that are relevant to practically calculating the limiting Pasquali patch. (See accompanying **Figure 7** and **Figure 8**)

**Remark 2.3.** (*December 8, 2012*) Suppose that, by some sorcery or heuristics or good guess, we have found a candidate probability distribution  $a(x)$  so that it is fixed for a given Pasquali patch  $p(x, y)$ . We can hazard the very good guess that the stationary limiting surface is  $p_\infty(x) = a(x)$ , and this itself is a Pasquali patch. It is only a “very good guess” because we have shown this equation to be true for Pasquali patch power collections that converge uniformly. In order to be completely certain that  $p_\infty(x) = a(x)$ , we would have to show that the Pasquali patch power collection generated by  $p(x, y)$  possesses this property, a task left to, for example, a Weierstrass M-test. The property of uniform convergence becomes unduly burdensome (imagine having to show for each  $p(x, y)$  uniform convergence before we can conclude without a shadow of a doubt that the limiting Pasquali patch is  $p_\infty(x) = a(x)$ ).

We are left with two choices: either (1) we prove for **Construction 2.1** or some-such family of Pasquali patches the property of uniform convergence, thus limiting ourselves to the study of these particular Pasquali patches (seems overly restrictive from my viewpoint), or (2) we weaken the uniform convergence criterion to just convergence (of any sort). In essence, this second argument implies showing that the limit of the integrals of converging Pasquali patch powers generated by  $p(x, y)$  equals the integral of the limiting Pasquali patch: a revision of **Lemma 2.5** (and subsequent claims that use it). With this, we need only posit convergence and  $p_\infty(x) = a(x)$  automatically. This second approach is the one I’m most inclined for and working toward.

**Lemma 2.18.** (*December 3, 2012*) If the sequence  $p_n(x, y)$  of Pasquali patch powers converge ~~uniformly~~ to  $p_\infty(x, y)$ , then  $p_\infty(x, y)$  is a Pasquali patch.

**Proof** Suppose we have a collection of converging Pasquali patch powers generated by the Pasquali patch  $p(x, y)$ . They must converge to something, so call this  $p_\infty(x, y)$ . Next look at the sequence

$$\left\{ \int_0^1 p_n(x, y) dx \right\}_{n \in \mathbb{Z}^+} = \{1\}_n$$

The sequence is obviously bounded above, but in particular, the least upper bound  $b$  is 1. Similarly, the infimum is itself 1. Next let’s look at  $\int_0^1 p_\infty(x, y) dx = c$ . Suppose that  $c > b$ . Then there is an integral of some Pasquali patch power that must be greater than 1. But this is a contradiction, since all Pasquali patch power integrals are 1. Next suppose  $c < b$ . The issue is that the sequence  $\{1\}_n$  is never less than 1 either. Clearly  $c = b$  and we are done. □

Things that change with this amendment:

- Proof of **Claim 2.9**. Rather than having Case 2 be the space of ~~uniformly~~ convergent surfaces, it is for convergent surfaces. Also,  $p_\infty(x, y)$  is a Pasquali patch by **Lemma 2.18**.
- **Corollary 2.16**. Rather than being for ~~uniformly~~ convergent Pasquali patches, the corollary holds for convergent Pasquali patches: The proof holds with **Lemma 2.18**. This we shall call:

**Corollary 2.19.**

- **Corollary 2.17** Again, the corollary holds for convergent Pasquali patches and not just ~~uniformly~~ convergent ones. The proof holds with **Lemma 2.18**. This we shall call:

**Corollary 2.20.**

- **Guiding Maplet 2.2.** Wherever there is a ~~“convergence”~~ convergence, we can substitute just “convergence.” Wherever there is a **Lemma 2.5**, we can substitute it by **Lemma 2.18**. Wherever there is a **Corollary 2.16**, we can change it to **Corollary 2.19**, and wherever there is a **Corollary 2.17**, we can substitute it to **Corollary 2.20**.

**Remark 2.4.** (*December 16, 2012*) This is why **Example 2.2** actually has a limiting probability distribution. The Pasquali patch power collection does not converge uniformly (it converges at the nodes first, e.g.), and yet it stabilizes to the uniform Pasquali patch eventually.

A corollary to all this is:

**Corollary 2.21** (Entropy). (*December 16, 2012*)  $\exists a(x)$  so that  $a(x) \star p(x, y) = a(x)$  if and only if the powers of  $p(x, y)$  converge.

**Proof** We have:

$\Rightarrow$  Suppose not, that the powers  $p(x, y)$  do not converge. One way for this to happen and have  $\int_0^1 p(x, y) dx = 1$  is if the powers get stuck, for example, in a loop, so that, say,

$$p_{2n+1}(x, y) = p(x, y)$$

and

$$p_{2n}(x, y) = q(x, y)$$

and

$$p(x, y) \neq q(x, y)$$

Then by hypothesis  $a(x) \star p_{2n+1}(x, y) = a(x)$  and it must also be true that  $a(x) \star p_{2n}(x, y) = a(x)$  for this same  $a(x)$  (**Claim 2.12**). This implies that  $a(x) \star p(x, y) = a(x)$  and  $a(x) \star q(x, y) = a(x)$ . Now each even powers and odd powers are independently convergent,  $p_{2n+1}(x, y)$  to  $p(x, y)$  and  $p_{2n}(x, y)$  to  $q(x, y)$ , which implies that  $a(x) = p(x, y)$  in the first case and  $a(x) = q(x, y)$  in the second case (**Corollary 2.19**). Other than the fact that both  $p(x, y)$  and  $q(x, y)$  could be functions of  $x, y$ , they are defined to be unequal to each other. We have a contradiction.

Next, let's make the loop larger. Suppose that the powers oscillate in  $k$  different surface forms, so that we have  $p^1(x, y) \dots p^k(x, y)$  surfaces after which we return to the original. The above would mean that  $p_n(x, y) = p^{n \bmod k}(x, y)$ . Each “in-between” power is independently convergent to itself after  $k$  more powers, and  $a(x) = p^k(x, y)$  due to **Corollary 2.19**. But these surfaces were defined to be different from each other, and so, as before, we face a contradiction.

We show of course the  $k + 1$  case. Suppose the powers oscillate in  $k + 1$  different surface forms, with

$$p^1(x, y) \dots p^{k+1}(x, y)$$

surfaces after which we return to the original. Then

$$p_n(x, y) = p^{n \bmod (k+1)}(x, y)$$

with each in-between power independently convergent to itself after  $k+1$  more powers, and  $a(x) = p^{k+1}(x, y)$  due to **Corollary 2.19** each. Each of these surfaces was different. We have a contradiction.

Now we can make the periodicity as large as we like.

This same argument applies for the case in which the oscillatory pattern is established (independently) to  $m$  different surfaces eventually. Suppose that we have  $p^1(x, y) \dots p^m(x, y)$  surfaces toward which each periodic sequence  $p_{n \bmod m}(x, y)$  converges eventually, with

$$\lim_{n \rightarrow \infty} p_{n \bmod m}(x, y) = p^{n \bmod m}(x, y)$$

An argument with respect to  $a(x)$  and the surfaces of convergence being unequal leads us to contradict, even inductively, that such a scenario is a possibility. An eventual convergent loop cannot form, no matter how large the loop or how slow or fast each convergence.

We have shown essentially that we cannot have an  $a(x)$  and have the *Pasquali patch* powers of  $p(x, y)$  oscillate in any shape or form in the long run.

We have not shown the “divergent” situation, in which the value of at least one point  $p_n(\bar{x}, \bar{y}) \rightarrow \infty$ . In particular, the product  $a(1 - \bar{y}) \cdot p_n(\bar{x}, \bar{y}) \rightarrow \infty$ , and the value of the integral  $\int_0^1 a(1 - y) \cdot p_n(\bar{x}, y) dy \rightarrow \infty$



as well. Thus  $a(\bar{x})$  diverges and  $a(x)$  was never bounded or well-behaved (Contradicting **Conjecture 2.1** regarding  $a(x)$ ). NB: This argument can probably be made more rigorous.

Lastly, since the powers neither stabilize oscillatorily nor can they diverge, they must converge.

⇐ (**December 24, 2012**) Since the powers of  $p(x, y)$  converge, they converge to  $p_\infty(x)$  by **Claim 2.9**, a function of  $x$  alone or constant for all  $x, y$ . Then it is certainly true that  $p(x, y) \star p_\infty(x) = p_\infty(x)$  by **Claim 2.7**. It must also be true by the same claim that  $p_\infty(x) \star p_\infty(x) = p_\infty(x)$ . If we substitute one equation into the other, we get  $p_\infty(x) \star (p(x, y) \star p_\infty(x)) = p_\infty(x)$ . By **Claim 1.8, Associativity of the Star Product**, we can rewrite that as  $(p_\infty(x) \star p(x, y)) \star p_\infty(x) = p_\infty(x)$ . But now the arguments in parenthesis must be equal to  $p_\infty(x)$ , in other words,  $p_\infty(x) \star p(x, y) = p_\infty(x)$ . Thus  $p_\infty(x)$  is fixed for  $p(x, y)$ . Let  $a(x)$  be exactly this  $p_\infty(x)$  and we are done. □

**Remark 2.5.** (*December 24, 2012*) *It is now evident that, so long as we can find a fixed  $a(x)$ , we know that the powers of  $p(x, y)$  (1) converge, (2) the stationary surface is  $p_\infty(x)$ , that (3)  $a(x) = p_\infty(x)$ , and (4)  $a(x)$  is fixed for all powers, including the stationary surface itself. Conversely, if we know that  $p_\infty(x)$  for some  $p(x, y)$ , then such is in fact  $a(x)$ . Our efforts from now on should focus on establishing a mechanism to find such  $a(x)$ .*

## 2.6. Fixed Distribution Existence.

**Claim 2.22.** (*December 2, 2012*) *For Construction 2.1,  $a(x)$  exists provided  $B = a(x) \star g_1(y)$  converges and can be solved. Its explicit form is*

$$a(x) = p_\infty(x) = \frac{f_2(x)}{F_2} - \left( \frac{f_2(x)F_1}{F_2} - f_1(x) \right) B$$

**Proof** We are looking for  $a(x)$  so that  $a(x) \star p(x, y) = a(x)$ , with

$$p(x, y) = f_1(x)g_1(y) + f_2(x) \left( \frac{1 - g_1(y)F_1}{F_2} \right)$$

Using the definition of the star operator (**Definition 1.1**), this is

$$\int_0^1 a(1-y) \left( f_1(x)g_1(y) + f_2(x) \left( \frac{1 - g_1(y)F_1}{F_2} \right) \right) dy = a(x)$$

Expansion results in:

$$a(x) = f_1(x) \int_0^1 a(1-y)g_1(y) dy + \frac{f_2(x)}{F_2} \cdot 1 - \frac{F_1}{F_2} f_2(x) \int_0^1 a(1-y)g_1(y) dy$$

where we have simplified  $\int_0^1 a(1-y) dy$  to 1 because the transformation to the  $y$ -axis does not change the integral result (it remains a probability distribution).

Rearranging, we have

$$\frac{f_2(x)}{F_2} - \left( \frac{f_2(x)F_1}{F_2} - f_1(x) \right) \int_0^1 a(1-y)g_1(y) dy$$

or

$$a(x) = \frac{f_2(x)}{F_2} - \left( \frac{f_2(x)F_1}{F_2} - f_1(x) \right) B = p_\infty(x)$$

(**Remark 2.5**) and derivatives

$$a^i(x) = \frac{f_2^i(x)}{F_2} - \left( \frac{f_2^i(x)F_1}{F_2} - f_1^i(x) \right) B$$

We want to obtain  $B$ , but the expression  $\int_0^1 a(1-y)g_1(y) dy$  has to be clearly defined. We use the tabular method to simplify the integration by parts.

Derivatives	Integrals
$a(1-y)$	$g_1(y)$
$-a'(1-y)$	$G_1^1(y)$
$a(1-y)$	$G_1^2(y)$
$\vdots$	$\vdots$

Viewed from a different vantage-point, we could have

Derivatives	Integrals
$g_1(y)$	$a(1-y)$
$g_1'(y)$	$-A^1(1-y)$
$g_1''(y)$	$A^2(1-y)$
$\vdots$	$\vdots$

Lastly, we have:

$$B = a(1-y)G_1^1(y) + a'(1-y)G_1^2(y) + \dots \Big|_0^1 = \sum_{i=0}^{\infty} a^i(1-y)G_1^{i+1}(y) \Big|_0^1$$

or

$$B = -g_1(y)A^1(1-y) - g_1'(y)A^2(1-y) - \dots \Big|_0^1 = -\sum_{i=0}^{\infty} g_1^i(y)A^{i+1}(1-y) \Big|_0^1$$

If the sum diverges we are stuck, but if the sum converges we are good.  $\square$

**Corollary 2.23.** (*December 25, 2012*) Pasquali patches constructed as by **Construction 2.1** with (finite) polynomial function choices for  $f_1(x)$  and  $f_2(x)$  are guaranteed to have a fixed  $a(x) = p_{\infty}(x)$  regardless of (integrable) function choice  $g_1(y)$ . Similarly, **Construction 2.1** Pasquali patches with a (finite) polynomial choice for  $g_1(y)$  are guaranteed to have such fixed  $a(x)$  as well, regardless of (integrable) function choices for  $f_1(x)$  and  $f_2(x)$ .

**Proof** Since

$$B = a(1-y)G_1^1(y) + a'(1-y)G_1^2(y) + \dots \Big|_0^1 = \sum_{i=0}^{\infty} a^i(1-y)G_1^{i+1}(y) \Big|_0^1$$

and the derivatives of  $a(x)$  are eventually zero (for all subsequent derivatives), the sum itself is finite. Thus,  $B$  converges, which implies that **Claim 2.22** applies.

Next, since

$$B = -g_1(y)A^1(1-y) - g_1'(y)A^2(1-y) - \dots \Big|_0^1 = -\sum_{i=0}^{\infty} g_1^i(y)A^{i+1}(1-y) \Big|_0^1$$

and the derivatives of  $g_1(y)$  are eventually zero (including all subsequent derivatives), such sum is also finite and  $B$  converges. Again, **Claim 2.22** applies.  $\square$

**Example 2.4.** (*January 16, 2011*) In **Example 2.1**, we had the Pasquali patch

$$p(x, y) = x^2y^3 + x \left( 2 - \frac{2y^3}{3} \right)$$

with  $f_1(x) = x^2$ ,  $f_2(x) = 2x$ ,  $g_1(y) = y^3$ . This implies by **Claim 2.22** that

$$a(x) = p_{\infty}(x) = 2x - \left( \frac{2x}{3} - x^2 \right) B$$

with derivatives

$$a'(x) = 2 - \left( \frac{2}{3} - 2x \right) B$$

$$a''(x) = -2B$$

Specifically,

$$\begin{aligned} a(1) &= 2 + \frac{B}{3} & \text{and} & & a(0) &= 0 \\ a'(1) &= 2 + \frac{4B}{3} & \text{and} & & a'(0) &= 2 - \frac{2B}{3} \\ a''(1) &= -2B & \text{and} & & a''(0) &= -2B \end{aligned}$$

Next, we want to calculate  $B$ :

$$B = \cancel{a(0)G_1^1(1)} + a'(0)G_1^2(1) + a''(0)G_1^3(1) - \left( \cancel{a(1)G_1^1(0)} + \cancel{a'(1)G_1^2(0)} + \cancel{a''(1)G_1^3(0)} \right)$$

The parenthetical part dies because integrals of  $y^3$  evaluated at 0 vanish. So does the first term since  $a(0) = 0$ . So we are left with:

$$B = a'(0)G_1^2(1) + a''(0)G_1^3(1) = \frac{6-2B}{3} \cdot \frac{1}{20} + -2B \cdot \frac{1}{120}$$

which solves

$$B = \frac{6}{63} = \frac{2}{21}$$

Thus, we have that

$$a(x) = p_\infty(x) = 2x - \left(\frac{2x}{3} - x^2\right) \frac{2}{21} = \frac{2x^2}{21} + \frac{122x}{63}$$

For a consistency check, by **Lemma 2.18** this is a Pasquali patch and therefore

$$\int_0^1 \left(\frac{2x^2}{21} + \frac{122x}{63}\right) dx = 1$$

can be verified to indeed be the case.

**Remark 2.6.** Practically speaking, all functions  $f(x), g(y)$  with Taylor polynomial representations in the domain  $[0, 1]$  will converge (just truncate them at the appropriate precision, e.g.).

## 2.7. Probability Distribution Transformations via Pasquali Patch Power Collections.

**Claim 2.24.** (January 12, 2013) Take a Pasquali patch power collection union its limiting surface,  $\mathbb{P} \cup p_\infty(x) = \mathbb{P}^\infty$ , and a well-behaved, bounded probability distribution  $c(x)$ , with  $c: [0, 1] \rightarrow \mathbb{R}^+ \cup \{0\}$ , and  $\int_0^1 c(x) dx = 1$ . Then  $c(x) \star \mathbb{P}^\infty = \mathbb{C}$  is a collection of transformed probability distributions of  $x$  (explicit or not).

**Proof by Induction** The proof consists of two cases.

Case 1. The generator of  $\mathbb{P}^\infty$  is a Pasquali patch function of  $x$  alone (explicitly or constant). Then, by **Claim 2.8** all Pasquali patches in the collection are functions of  $x$  (explicitly or constant), and in fact all powers in  $\mathbb{P}$  equal  $p(x)$ , including  $p_\infty(x)$  (**Case 1 of Claim 2.9**). Begin with

$$c(x) \star P^1 = c(x) \star p(x) = p(x)$$

by **Claim 2.7**. Assume that  $c(x) \star P^k = p(x)$ . Then

$$c(x) \star P^{k+1} = c(x) \star (P^1 \star P^k) = c(x) \star (P^k \star P^1) = (c(x) \star P^k) \star p(x) = p(x) \star p(x) = p(x)$$

We used **Claim 1.9 Powering Symmetry** to exchange the order of the powers, **Claim 1.8 Associativity of the Star Product**, and again by **Claim 2.7** the last equality holds. Furthermore, since  $p_\infty(x) = p(x)$ ,  $c(x) \star p_\infty(x) = c(x) \star p(x) = p(x)$ . This last part is justified by **Claim 2.7** once more. Thus,  $c(x) \star \mathbb{P}^\infty = \mathbb{C} = \{p(x)\}$  and all functions are explicit functions of  $x$  or constant as we wanted to show. By **Claim 2.10**, the collection is made up of probability distributions on  $[0, 1]$ .

Case 2. The generator of  $\mathbb{P}^\infty$  is a Pasquali patch function of  $y$  explicitly. Begin by

$$c(x) \star P^1 = \int_0^1 c(1-y)p(x, y) dy = c_1(x)$$

Since we are integrating with respect to  $y$  we can see that this function  $c_1(x)$  is either explicitly function of  $x$  or constant. Next assume that  $c(x) \star P^k = c_k(x)$  is an explicit function of  $x$  or constant. Then

$$c(x) \star P^{k+1} = c(x) \star P^{1+k} = c(x) \star (P^k \star P^1) = (c(x) \star P^k) \star P^1 = c_k(x) \star P^1$$

This last part is  $\int_0^1 c_k(1-y)p(x, y) dy$ , which, by virtue of integrating in terms of  $y$  yields an explicit function of  $x$  or constant. Now take  $c(x) \star p_\infty(x) = p_\infty(x)$  by **Claims 2.9** and **2.7**. Thus, all functions in the collection  $c(x) \star \mathbb{P}^\infty = \mathbb{C}$  are explicit functions of  $x$  or constant. Finally, by **Claim 2.10**, the collection is made up of probability distributions on  $[0, 1]$ . □

**Claim 2.25.** (January 12, 2013) Let  $c(x) \star P^m = c_m(x)$ , the  $m$ th transform of  $c(x)$  via the  $m$ th power of  $p(x, y)$ . An equivalent way to obtain the  $m$ th transform is by  $c_{m-1}(x) \star P^1 = c_m(x)$ .

**Proof by Induction** Begin by  $c(x) \star P^1 = c_1(x)$  using the first statement and  $c_0(x) \star P^1 = c_1(x)$  using the second statement. Clearly the two statements are equivalent. Next, assume that the statement holds for the  $k$ th transform, so that  $c(x) \star P^k = c_k(x)$  and  $c_{k-1}(x) \star P^1 = c_k(x)$ . Now  $c(x) \star P^{k+1} = c_{k+1}(x)$  by definition. An equivalent way to write this is

$$c(x) \star P^{1+k} = c(x) \star (P^k \star P^1) = (c(x) \star P^k) \star P^1 = c_k(x) \star P^1$$

Here we have used **Claim 1.8 Associativity of the Star Product**. Thus  $c_k(x) \star P^1 = c_{k+1}(x)$ , and we are done.  $\square$

**Claim 2.26.** (*January 13, 2013*) *The collection  $\mathbb{C}$  converges to  $p_\infty(x)$ .*

**Indirect Proof 1** Suppose  $\lim_{m \rightarrow \infty} c_m(x) \neq p_\infty(x)$ . Then

$$\left[ \lim_{m \rightarrow \infty} c_m(x) \right] \star p_\infty(x) \neq p_\infty(x) \star p_\infty(x)$$

and

$$p_\infty(x) \neq p_\infty(x) \star p_\infty(x)$$

is a contradiction of **Claim 2.8** or **Claim 2.7**. Thus  $\lim_{m \rightarrow \infty} c_m(x) = p_\infty(x)$ .  $\square$

**Indirect Proof 2** Suppose that the sequence of probability distributions  $c_m(x)$  diverge, that

$$\lim_{m \rightarrow \infty} c_m(\bar{x}) = \infty$$

for some  $\bar{x}$ . This would have to mean that  $\lim_{m \rightarrow \infty} \int_0^1 c(1-y)p_m(\bar{x}, y) dy = \infty$ . But then the sequence  $p_m(\bar{x}, y)$  would have to be divergent, because  $c(x)$  is chosen to be well-behaved and bounded. We have a contradiction, because the sequence  $p_m(x, y)$  is well-behaved and bounded by virtue of being *Pasquali patch* powers with bounded first-power generator and fixed volume. Thus  $\lim_{m \rightarrow \infty} c_m(x)$  converges.

Next suppose the sequence of probability distributions  $c_m(x)$  does not converge to  $p_\infty(x)$  but to some other probability distribution in the collection  $\mathbb{C}$ , say  $c_k(x)$ . The issue is this isn't an accumulation probability distribution, since we can generate  $c_{k+1}(x)$  by starring by  $P^1$  on the right (**Claim 2.25**). Lastly, say we choose a probability distribution outside of the collection  $\mathbb{C}$ , in some other collection  $\mathbb{D}$ . If we choose  $d_k(x)$ , this isn't an accumulation probability distribution for  $\mathbb{C}$  because it was generated by *Pasquali patch*  $q(x, y)$ , and also  $d_{k+1}(x)$  can be generated by right-starring by  $Q^1$ . Then pick  $p_\infty^d(x)$ , the limiting probability distribution in  $\mathbb{D}$ . There's just no way to tie such to the generator collection  $\mathbb{P}^\infty$ , since it is an accumulation probability distribution for  $\mathbb{D}$ , not for  $\mathbb{C}$ . The only choice left (that makes sense) is  $p_\infty^c(x)$ .  $\square$

**Corollary 2.27.** (*January 13, 2013*)

$$\lim_{m \rightarrow \infty} c_m(x) = p_\infty(x)$$

if and only if

$$\lim_{m \rightarrow \infty} [c(x) \star P^m] = c(x) \star \left[ \lim_{m \rightarrow \infty} P^m \right]$$

In other words, we can pull the limiting process under the integral.

**Proof** We have:

$\Rightarrow$  By definition,  $c(x) \star P^m = c_m(x)$ . Then

$$\lim_{m \rightarrow \infty} c_m(x) = \lim_{m \rightarrow \infty} [c(x) \star P^m] = p_\infty(x)$$

by hypothesis.

Next,

$$\lim_{m \rightarrow \infty} [c(x) \star P^m] = \lim_{m \rightarrow \infty} \int_0^1 c(1-y)p_m(x, y) dy = p_\infty(x)$$

An equivalent expression can be found through **Claim 2.7**:

$$p_\infty(x) = \int_0^1 c(1-y)p_\infty(x) dy$$

This is,

$$p_\infty(x) = \int_0^1 c(1-y) \left[ \lim_{m \rightarrow \infty} p_m(x, y) \right] dy$$

In other words, we now have

$$p_\infty(x) = c(x) \star \left[ \lim_{m \rightarrow \infty} P^m \right]$$

Putting these two expressions together yields the desired result.

⇐ Take

$$c(x) \star \left[ \lim_{m \rightarrow \infty} P^m \right] = c(x) \star p_\infty(x) = p_\infty(x)$$

by definition of the limiting surface and **Claim 2.7**. The alternative way to write this by the stated equality in the hypothesis is:

$$\lim_{m \rightarrow \infty} [c(x) \star P^m] = p_\infty(x)$$

In turn, this can be written as  $\lim_{m \rightarrow \infty} c_m(x) = p_\infty(x)$  by definition and we are done. □

**Corollary 2.28.** (*January 15, 2013*)

$$\lim_{m \rightarrow \infty} \int_0^1 p_m(x, y) dy = p_\infty(x) = \lim_{m \rightarrow \infty} p_m(x, y)$$

**Proof** Take  $c(x) = u(x)$ , the uniform probability distribution, which equals 1 for all  $x$  in the domain. We can then state by **Corollary 2.27** that

$$\lim_{m \rightarrow \infty} [1 \star P^m] = 1 \star \left[ \lim_{m \rightarrow \infty} P^m \right]$$

which is equivalent to:

$$\lim_{m \rightarrow \infty} \int_0^1 p_m(x, y) dy = \int_0^1 \lim_{m \rightarrow \infty} p_m(x, y) dy$$

which, in turn, yields

$$\lim_{m \rightarrow \infty} \int_0^1 p_m(x, y) dy = p_\infty(x) = \lim_{m \rightarrow \infty} p_m(x, y)$$
□

**Remark 2.7.** (*January 15, 2013*) We now have that

$$\lim_{m \rightarrow \infty} \int_0^1 p_m(x, y) dx = 1$$

by **Definition 2.1** and **Claim 2.1 Closure of Pasquali Patches** and

$$\lim_{m \rightarrow \infty} \int_0^1 p_m(x, y) dy = p_\infty(x)$$

by **Corollary 2.28**.

**Corollary 2.29.** (*January 13, 2013*)

$$\lim_{m \rightarrow \infty} c_m(x) = p_\infty(x)$$

if and only if

$$\lim_{m \rightarrow \infty} [c_{m-1}(x) \star P^1] = \left[ \lim_{m \rightarrow \infty} c_{m-1}(x) \right] \star P^1$$

**Proof** This follows from **Claim 2.25**. □

**Corollary 2.30.** (*January 13, 2013*)

$$\lim_{m \rightarrow \infty} c_m(x) = p_\infty(x)$$

if and only if

$$c(x) \star \left[ \lim_{m \rightarrow \infty} P^m \right] = \left[ \lim_{m \rightarrow \infty} c_{m-1}(x) \right] \star P^1$$

In other words,

$$c(x) \star p_\infty(x) = c_\infty(x) \star P^1$$

**Proof** This follows from **Corollary 2.27** and **Corollary 2.29**. □

## 2.8. More on *Pasquali Patch Powers and Limiting Surfaces*.

**Remark 2.8.** (*January 13, 2014*) The following claims and proofs are applicable to Pasquali patches as they are to Markov matrices, where we shift from a function point-of-view to a matricial point-of-view using in one the star product and in the other normal matrix multiplication.

**Claim 2.31.** (*January 13, 2014*) Take the countably infinite collections of Pasquali patch self-powers  $\mathbb{P} = \{P^1, P^2, \dots, P^j, \dots\}_{j \in \mathbb{Z}^+}$  and  $\mathbb{Q} = \{Q^1, Q^2, \dots, Q^k, \dots\}_{k \in \mathbb{Z}^+}$  with stationary limiting  $P^\infty$  and  $Q^\infty$  respectively. If  $\mathbb{P}$  and  $\mathbb{Q}$  coincide at  $(m, n)$  so that  $P^m = Q^n$  ( $\frac{n}{m} \in \mathbb{Z}^+$ ) then  $P^\infty = Q^\infty$ .

**Proof** The infinite collections coincide at  $(m, n)$  for  $m, n, \frac{n}{m} \in \mathbb{Z}^+$ , thus we have that  $P^m = Q^n$ . By **Claim 1.13** we have that  $\mathbb{P}_m \subset \mathbb{Q}_n$ . Now the limit  $\lim_{n \rightarrow \infty} Q_n = Q^\infty$  by hypothesis of the existence of the stationary patch, and since  $\mathbb{P}_m$  is a subset of  $\mathbb{Q}_n$ , it follows that  $\lim_{m \rightarrow \infty} P_m = Q^\infty$ . We also know that  $\lim_{m \rightarrow \infty} P_m = P^\infty$  however (again by hypothesis of the existence of the stationary patch), so it must therefore be true that  $P^\infty = Q^\infty$ .  $\square$

The reverse claim is not (always) true:

**Claim 2.32** (False Claim). (*January 13, 2014*) If  $P^\infty = Q^\infty$ , then  $\mathbb{P}$  and  $\mathbb{Q}$  coincide at  $(m, n)$  so that  $P^m = Q^n$  ( $\frac{n}{m} \in \mathbb{Z}^+$ ).

**Disproof** Take the collection of *Pasquali patches*  $\mathbb{P} = \{P^1 = 1, P^2 = 1, \dots, P^j = 1, \dots\}_{j \in \mathbb{Z}^+}$  with  $P^\infty = 1$ , and any collection of *Pasquali patches*  $\mathbb{Q} = \{Q^1, Q^2, \dots, Q^k, \dots\}_{k \in \mathbb{Z}^+}$  so that the generator  $Q^1 = q(x, y)$  is an explicit function of  $y$  and  $Q^\infty = 1$ , as in **Example 2.2**. By **Claim 2.6**, all elements in the collection  $\mathbb{Q}$  are explicit functions of  $y$  (even as  $Q^\infty$  is not by **Claim 2.9**). Clearly, no  $P \in \mathbb{P}$  is equal to an element  $Q \in \mathbb{Q}$  (all  $P$  are constant where all  $Q$  vary with  $y$ ), yet they have the same stationary patch.  $\square$

## 2.9. Even More on *Pasquali Patches and Limiting Surfaces*.

### 2.9.1. Preparatory Claims.

**Claim 2.33.** (*May 5, 2014*) Take  $f_i(x) = (i+1)x^i$  with  $i \in \mathbb{Z}^+ \cup \{0\}$ . Then  $\int_0^1 f_i(x) dx = 1, \forall i$ .

**Proof by Induction** Using the definition of integration of powers of  $x$ , we show that  $\int_0^1 f_0(x) dx = 1$ . The expression equals

$$\int_0^1 x^0 dx = \int_0^1 1 dx = x \Big|_0^1 = 1$$

We assume that the  $k$ th element  $\int_0^1 f_k(x) dx = 1$  although we readily know by the definition of integration that such is true, since

$$\int_0^1 (k+1)x^k dx = x^{k+1} \Big|_0^1 = 1^{k+1} = 1$$

The exact same definition argument applies to the  $k+1$ th element and

$$\int_0^1 (k+2)x^{k+1} dx = x^{k+2} \Big|_0^1 = 1^{k+2} = 1$$

$\square$

**Claim 2.34.** (*May 5, 2014*) The functions  $f_i(x) = (i+1)x^i$  with  $i \in \mathbb{Z}^+ \cup \{0\}$  are Pasquali patches.

**Proof** A *Pasquali patch* is a function  $p(x, y)$  so that  $\int_0^1 p(x, y) dx = 1$  by **Definition 2.1**. Let  $p(x, y) = f_i(x)$ . Since by **Claim 2.33**  $\int_0^1 f_i(x) dx = 1, \forall i = 1 \dots n$ , then applying the definition means  $f_i(x) = (i+1)x^i$  are Pasquali patches  $\forall i \in \mathbb{Z}^+ \cup \{0\}$ .  $\square$

**Claim 2.35.** (*May 5, 2014*) The finite polynomial  $g(x) = \sum_{i=0}^n (i+1)x^i$  converges in area from  $[0, 1]$  to  $n+1$ .

**Proof** We are looking for

$$\int_0^1 \sum_{i=0}^n (i+1)x^i dx$$

The sum is finite so it converges, and there is no issue exchanging the order of the sum and integral. Thus:

$$\sum_{i=0}^n \int_0^1 (i+1)x^i dx = \sum_{i=0}^n \left( x^{i+1} \Big|_0^1 \right) = \sum_{i=0}^n 1^{i+1} = \sum_{i=0}^n 1 = n+1$$

$\square$

**Claim 2.36.** (May 5, 2014) Pick  $n$  functions from the pool of  $f_i(x) = (i + 1)x^i$ . For example, pick  $f_3(x), f_5(x)$ , and  $f_7(x)$ . Create the function  $h(x) = \sum_i f_i(x)$ . Then  $\int_0^1 h(x) dx = n$ .

**Proof by Induction** Since by **Claim 2.34** all  $f_i(x)$  are *Pasquali patches*, it follows their integral is 1 in the interval (**Claim 2.33**). Picking 1 function from the pool thus gives an integral of 1 in the interval. Suppose that picking  $k$  functions gives  $k$  units at the integral in the interval. Now pick  $k + 1$  functions. The first  $k$  functions give  $k$  units at the integral in the interval, and the 1 additional function contributes 1 unit at the integral in the interval. Thus  $k + 1$  functions contribute  $k + 1$  units at the integral in the interval.  $\square$

**Corollary 2.37.** (May 5, 2014) The infinite polynomial  $a(x) = \sum_{i=0}^{\infty} (i + 1)x^i$  diverges in area in the interval from  $[0, 1]$ .

**Proof** Take

$$\int_0^1 \left( \lim_{n \rightarrow \infty} \sum_{i=0}^n (1 + i)x^i \right) dx = \lim_{n \rightarrow \infty} \int_0^1 \sum_{i=0}^n (1 + i)x^i dx$$

Here exchanging the order of limit and integral is justified by the fact that, term-wise, the integral converges. Next

$$\lim_{n \rightarrow \infty} n + 1 = \infty$$

Here the second to last step is justified by **Claim 2.35**.

**Corollary 2.38.** (May 5, 2014) The infinite polynomial  $a(x) - h(x)$  diverges in area in the interval from  $[0, 1]$ .

**Proof** Take the limit

$$\lim_{n \rightarrow \infty} [a(x) - h(x)]$$

Taking  $n$  to infinity applies to  $a(x)$  only which we know diverges by **Corollary 2.37**. The same limit has no effect on  $h(x)$  as the sum it is composed of is finite and adds up to an integer constant, say  $m$ . We conclude that any infinite collection of terms of  $f_i(x)$  diverges, even when a finite number of them may be absent from the sum.  $\square$

**Corollary 2.39.** (May 5, 2014) The infinite polynomial  $a(x) - b(x)$  diverges in area in the interval from  $[0, 1]$  with  $a(x), b(x)$  are infinite polynomials constructed by sums of functions picked from the pool  $f_i(x) = (i + 1)x^i$  and with no repetitions. (Note that the difference of these two infinite polynomials must also be infinite).

**Proof** Since the  $a(x) - b(x)$  is an infinite polynomial, the integral of such will be an infinite string of ones since the functions it contains are  $f_i(x)$  and these are *Pasquali patches* (**Claim 2.34**) and there are no repetitions. Such infinite sum of ones clearly diverges.  $\square$

**Remark 2.9.** (May 5, 2014) We can view what we have learned in the claims from a slightly different vantage point. Create the infinite identity matrix

$$I = \begin{bmatrix} 1 & 0 & 0 & \dots \\ 0 & 1 & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

Next create the following polynomial differential vector

$$D = \begin{bmatrix} 1 \\ 2x \\ 3x^2 \\ \vdots \end{bmatrix}$$

It is clear that

$$\int_0^1 I_i \cdot D dx = 1$$

for all rows  $i$  of  $I$ . We can omit the little  $i$  because this definition applies to all rows and:

$$\int_0^1 I \cdot D dx = \int_0^1 D dx = \begin{bmatrix} 1 \\ 1 \\ \vdots \end{bmatrix} = \mathbf{1}$$

This of course summarizes **Claim 2.33** and **Claim 2.34**. Next, define the matrix  $J$  consisting of rows which are finite sums of rows of  $I$  (so that each row of  $J$  consists of a finite number of ones at any position, namely  $n$  such coming from  $n$  picked rows of  $I$ ). **Claim 2.35** and **Claim 2.36** are summarized in the statement

$$\int_0^1 J \cdot D \, dx = S$$

where  $S$  is the vector consisting of the sum of the rows of  $J$ , which, since it is made up of a finite number of ones at each row, adds up to a constant integer at each row:

$$S = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \end{bmatrix}$$

Finally, the corollaries can be summarized in the statement in which we create a matrix  $K$  consisting of rows with a finite number of zeroes (and an infinite number of ones) or an infinite number of zeroes but an infinite number of ones as well. It is clear then that

$$\int_0^1 K \cdot D \, dx = \infty$$

**Remark 2.10.** (May 5, 2014) The cool thing about this notation is that it gives us power to conclude several interesting things. For example, scaling of matrices  $I$  and  $J$  as by a constant  $t$  shows convergence at the integral in the interval  $[0, 1]$  of every one of the scaled sums represented by the rows of such matrices.

Thus:

**Corollary 2.40.** (May 5, 2014) Let  $I^* = t \cdot I$  and  $J^* = t \cdot J$  with  $t$  is a scaling factor. Then the area of each of the infinitely many polynomials represented by the matrices  $I^*, J^*$  dot  $D$  in the interval from 0 to 1 converge.

**Proof** On the one hand, we have

$$\int_0^1 I^* \cdot D \, dx = \int_0^1 t \cdot I \cdot D \, dx = t \left( \int_0^1 I \cdot D \, dx \right) = t$$

On the other hand,

$$\int_0^1 J^* \cdot D \, dx = \int_0^1 t \cdot J \cdot D \, dx = t \left( \int_0^1 J \cdot D \, dx \right) = t \cdot S = \begin{bmatrix} t \cdot n_1 \\ t \cdot n_2 \\ \vdots \end{bmatrix}$$

□

**Remark 2.11.** (May 5, 2014) Next consider the infinite-matrix formed by convergent sequences (at the sum) at each row,

$$A = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots \\ 1 & \frac{1}{2^2} & \frac{1}{3^2} & \dots \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix}$$

Depicted is the reciprocals of squares which we know converges at the sum (Basel problem), simply for illustration, but all convergent sequences would be in the  $i$ th row of  $A$ . We have

$$\int_0^1 A_i \cdot D \, dx = \sum_j a_{i,j}$$

is convergent by definition. The cool thing is we can easily prove in one swoop that all sequences that are scaled will also converge at the sum (and the infinite polynomials with coefficients  $A \cdot D$  have converging area in the interval from 0 to 1).

**Corollary 2.41.** (May 5, 2014) Let  $A^* = t \cdot A$  with  $t$  is a scaling factor. Then the area of each of the infinitely many polynomials represented by the matrix entries of  $A^* \cdot D$  in the interval from 0 to 1 converge.



**Proof** We have

$$\int_0^1 A_i^* \cdot D \, dx = \sum_j a_{i,j}$$

for all  $i$ , so this equals

$$\int_0^1 t \cdot A_i \cdot D \, dx = t \left( \int_0^1 A_i \cdot D \, dx \right) = t \cdot \sum_j a_{i,j}$$

for all  $i$ .

All of these small and obvious observations lead to the following Claim.

2.9.2. *Classifying Pasquali Patches that are Functions of  $x$  Alone.*

**Claim 2.42** (The Grand Classification Theorem: a General and Absolutely Complete Classification of *Pasquali Patches* which are Functions of  $x$  Alone). (**May 5, 2014**) All Pasquali patches which are functions of  $x$  alone (and therefore possible limiting surfaces) take the form

$$p(x) = \frac{A_i \cdot D}{\sum_j a_{i,j}}$$

**Proof** We have that, since such  $p(x)$  is a *Pasquali patch*, it must conform to **Definition 2.1**. Thus

$$\int_0^1 p(x) \, dx = \int_0^1 \frac{A_i \cdot D}{\sum_j a_{i,j}} \, dx = \frac{\int_0^1 A_i \cdot D \, dx}{\sum_j a_{i,j}} = \frac{\sum_j a_{i,j}}{\sum_j a_{i,j}} = 1$$

shows this is indeed the case. To show that all *Pasquali patches* that are functions of  $x$  alone are of the form of  $p(x)$ , we argue by contradiction. Suppose that there is a *Pasquali patch* that is a function of  $x$  alone which does not take the form of  $p(x)$ . It couldn't possibly be one such that is a finite polynomial, since  $A_i$  was defined to be that matrix formed by all convergent sequences at the sum at each row and it can be scaled any which way we like, and this includes sequences with a finite number of nonzero coefficients. But now it couldn't be any infinite polynomial either, by the same definition of  $A_i$  which includes infinite sequences so that  $\sum_j a_{i,j}$  is convergent. Thus it must be a polynomial formed by dotting divergent sequences (at the sum), but all such have been happily excluded from the definition of  $A$ .  $\square$

**Remark 2.12.** (**May 5, 2014**) Thus, EVERY convergent series has an associated Pasquali patch which is solely a function of  $x$ , and vice versa, covering the totality of the Pasquali patch functions of  $x$  universe and the convergent series universe bijectively once we take into account equivalence classes (due to the normalization factor of the polynomial part). These equivalence classes will be described presently.

**Claim 2.43.** (**August 12, 2014**) Take an element  $\omega_i \in \Omega$ , the set of (all) polynomials that can be generated by a convergent sequence as defined above (that is, the set of polynomials that converge in area in the interval  $[0, 1]$ ). Define a relation on  $\Omega$  by setting  $\omega_1 \sim \omega_2$  if

$$\frac{A_1}{\sum_j a_{1,j}} = \frac{A_2}{\sum_j a_{2,j}}$$

This in fact defines an equivalence relation on the set  $\Omega$ .

**Proof** The equivalence relation is defined by the rules (reflexivity, symmetry, transitivity) of equality. Thus we have:

- *Reflexivity.* Pick any  $\omega \in \Omega$ , and apply the definition of equivalence relation, so that

$$\frac{A_i}{\sum_j a_{i,j}} = \frac{A_i}{\sum_j a_{i,j}}$$

for any integer  $i$  that indexes the set. Reflexivity of the equivalence relation follows from reflexivity of equality.

- *Symmetry.* Pick  $(\omega_1, \omega_2) \in \Omega \times \Omega$  so that

$$\frac{A_1}{\sum_j a_{1,j}} = \frac{A_2}{\sum_j a_{2,j}}$$

or  $\omega_1 \sim \omega_2$ . It is easy to see that by the symmetric property of equality,

$$\frac{A_2}{\sum_j a_{2,j}} = \frac{A_1}{\sum_j a_{1,j}}$$

or  $\omega_2 \sim \omega_1$

- *Transitivity.* Pick  $(\omega_1, \omega_2), (\omega_2, \omega_3) \in \Omega \times \Omega$ , so that  $\omega_1 \sim \omega_2$  and  $\omega_2 \sim \omega_3$ . This translates to

$$\frac{A_1}{\sum_j a_{1,j}} = \frac{A_2}{\sum_j a_{2,j}}$$

and

$$\frac{A_2}{\sum_j a_{2,j}} = \frac{A_3}{\sum_j a_{3,j}}$$

By transitivity of equality, it follows that

$$\frac{A_1}{\sum_j a_{1,j}} = \frac{A_3}{\sum_j a_{3,j}}$$

or  $\omega_1 \sim \omega_3$ . □

**Example 2.5.** (*August 12, 2014*) Here we introduce notation for equivalent  $\omega \in \Omega$ . Suppose that in the  $\bar{i}$ th row of  $A$ , that is in  $A_{\bar{i}}$ , we have

$$A_{\bar{i}} = [ 1 \quad 1 \quad 0 \quad \dots ]$$

Let us agree that the notation

$$\omega [ 1 \quad 1 ] (x) = 1 + 2x$$

represents the polynomial generated by such. Then

$$\omega [ 1 \quad 1 ] (x) \sim \omega [ 2 \quad 2 ] (x) \sim \dots \sim \omega [ z \quad z ] (x)$$

with  $z \in \mathbb{R} \setminus \{0\}$  fall into the equivalence class represented by

$$\omega [ \frac{1}{2} \quad \frac{1}{2} ]^\circ (x) = \frac{1}{2} + x$$

We shall call this last polynomial the lowest terms polynomial, and it is easy to check that it in fact is in lowest terms by adding the entries between brackets. If the result is 1, it is. However we make explicit note of this by adding a circle at the top of the ending bracket (this can be especially useful when we have infinite polynomials, since this saves us the trouble of adding infinite sequences to ascertain equality to 1).

Next let us assume that we have an infinite sequence, such as  $\frac{1}{n^2}$ . We can write such as:

$$\omega [ \frac{1}{n^2} \Big|_1^\infty ] (x) = 1 + \frac{x}{2} + \frac{x^2}{3} + \frac{x^3}{4} + \dots$$

where the formula represents how we will write the entries, and the pipe represents the range of the index. We remark that this polynomial converges in area in the interval from  $[0, 1]$  (Basel problem), but particularly we would not represent polynomials in this way if we were not guaranteed convergence already of the sequence at the sum. Thus we emphasize that this notation is not for all polynomials. It is for polynomials that converge in area in the interval between  $[0, 1]$ : polynomials  $\omega(x)$ .

Lastly, if the sequence were a finite sequence with many (several) entries, we could write:

$$\omega [ \frac{1}{n^2} \Big|_1^4 ] (x) = 1 + \frac{x}{2} + \frac{x^2}{3} + \frac{x^3}{4}$$

**Definition 2.3.** (*August 13, 2014*) Define the binary operator  $\oplus$  on  $\Omega$ , so that  $\oplus: \Omega \times \Omega \rightarrow \Omega$  takes two polynomials  $\omega_1(x)$  and  $\omega_2(x)$  and converts them to another via addition of coefficients term-by-term.

**Claim 2.44.** (*August 13, 2014*) Suppose you have polynomials  $\omega_1(x)$  and  $\omega_2(x)$  that belong to the equivalence class represented by  $\omega^\circ(x)$ . Then  $\omega_1 \oplus \omega_2$  belongs to the same equivalence class. That is, all equivalence classes in  $\Omega$  are closed under  $\oplus$ .

**Proof** Let  $\omega_1(x) = \omega_{[\rho_1(n)]}(x)$  and  $\omega_2(x) = \omega_{[\rho_2(n)]}(x)$  belong to an equivalence class  $\omega^\circ(x)$ . Now  $\rho_1(n)$  and  $\rho_2(n)$  are functions on integer  $n$  and are indexed the same way since they belong to the same equivalence class. Thus  $\omega_{[\rho_1(n)]}(x) \oplus \omega_{[\rho_2(n)]}(x) = \omega_{[\rho_1(n)+\rho_2(n)]}(x)$ . Since  $\omega_{[\rho_1(n)]}(x) \sim \omega_{[\frac{\rho_1(n)}{\sum_n \rho_1(n)}]}(x)$ , and  $\omega_{[\rho_2(n)]}(x) \sim \omega_{[\frac{\rho_2(n)}{\sum_n \rho_2(n)}]}(x)$ ,

and  $\omega_{\left[\frac{\rho_1(n)}{\sum_n \rho_1(n)}\right]}(x) \sim \omega_{\left[\frac{\rho_2(n)}{\sum_n \rho_2(n)}\right]}(x)$  because they belong to the same equivalence class  $\omega^\circ(x)$ , it follows that  $\frac{\rho_1(n)}{\sum_n \rho_1(n)} = \frac{\rho_2(n)}{\sum_n \rho_2(n)}$ , or  $\rho_2(n) = r \cdot \rho_1(n)$  with  $r$  is the appropriate ratio of the sums.

Now we are in a position to show that  $\omega_{[\rho_1(n)+\rho_2(n)]}(x) \sim \omega^\circ(x)$ . We may calculate that  $\omega_{[\rho_1(n)+\rho_2(n)]}(x) \sim \omega_{\left[\frac{\rho_1(n)+\rho_2(n)}{\sum_n (\rho_1(n)+\rho_2(n))}\right]}(x)$ . In other words

$$\omega_{\left[\frac{\rho_1(n)+r \cdot \rho_1(n)}{\sum_n (\rho_1(n)+r \cdot \rho_1(n))}\right]}(x) = \omega_{\left[\frac{(r+1) \cdot \rho_1(n)}{(r+1) \sum_n \rho_1(n)}\right]}(x) = \omega_{\left[\frac{\rho_1(n)}{\sum_n \rho_1(n)}\right]}(x) \sim \omega^\circ(x)$$

We have thus shown closure within any equivalence class using the operation  $\oplus$ .  $\square$

**Definition 2.4.** (*August 13, 2014*) Let us define the equivalence class set on  $\Omega$ , that is, the union of all equivalence classes of  $\Omega$  that partition  $\Omega$ , by  $[\Omega]$ .

**Remark 2.13.** (*August 13, 2014*) All equivalence classes defined in **Claim 2.43**, are in fact (at least) magmas or grupoids. Put a different way, each set  $\omega_i^\circ \in [\Omega]$  ( $i \in \mathbb{R}$ ) are magmas or grupoids.

For any equivalence class  $\omega_i^\circ \in [\Omega]$  and operation  $(\omega_i^\circ, \oplus)$ , applying the definition of a magma or grupoid we have that:  $\forall \omega_1(x), \omega_2(x) \in \omega_i^\circ$ ,  $\omega_1 \oplus \omega_2 \in \omega_i^\circ$  rings true using closure on every equivalence class proven in **Claim 2.44**. Put a different way, each equivalence class is a magma or grupoid because each possesses the property of closure. In fact each equivalence class possesses the property of associativity with the operation  $\oplus$ , and thus are semigroups. If we take an identity element outside the semigroups and place it in each, each equivalence class can be made into a monoid. In fact in this new structure we can define inverses and make the equivalence classes into groups. All these facts we prove presently.

**Claim 2.45.** (*August 13, 2014*) Each set  $\omega_i^\circ \in [\Omega]$  possesses, independently, the property of associativity under  $\oplus$ .

**Proof** Pick any elements  $\omega_1(x), \omega_2(x), \omega_3(x) \in \omega_i^\circ$ . The fact that  $(\omega_1(x) \oplus \omega_2(x)) \oplus \omega_3(x) = \omega_1(x) \oplus (\omega_2(x) \oplus \omega_3(x))$  follows from associativity of the reals. Thus we have that

$$(\omega_{[\rho_1(n)]}(x) \oplus \omega_{[\rho_2(n)]}(x)) \oplus \omega_{[\rho_3(n)]}(x) = (\omega_{[\rho_1(n)+\rho_2(n)]}(x) \oplus \omega_{[\rho_3(n)]}(x) = \omega_{[\rho_1(n)+\rho_2(n)+\rho_3(n)]}(x)$$

On the other hand,

$$\omega_{[\rho_1(n)]}(x) \oplus (\omega_{[\rho_2(n)]}(x) \oplus \omega_{[\rho_3(n)]}(x)) = \omega_{[\rho_1(n)]}(x) \oplus (\omega_{[\rho_2(n)+\rho_3(n)]}(x)) = \omega_{[\rho_1(n)+\rho_2(n)+\rho_3(n)]}(x)$$

Of course all of these belong to the same equivalence class, and we are done. We have shown that each  $\omega_i^\circ \in [\Omega]$  is associative (and closed, **Claim 2.44**), and therefore a *semigroup*.  $\square$

**Definition 2.5.** (*August 13, 2014*) Define  $\omega_{[0]} \in \Omega$  to be the zero polynomial so that

$$\omega_{[0]} = \mathbf{0} = 0 + 0 \cdot x + 0 \cdot x^2 + \dots$$

Notice we cannot normalize the polynomial (we cannot divide by zero), so this element lies outside all equivalence classes contained in  $[\Omega]$ . However it does lie in  $\Omega$  because the sum of the zero entries converge (to zero).

**Remark 2.14.** (*August 13, 2014*) Notice how our information about  $\Omega$  is now complete, in that  $\Omega = [\Omega] \cup \omega_{[0]}$ .

**Claim 2.46.** (*August 13, 2014*) Take any equivalence class union the zero polynomial  $\omega_i^\circ \cup \omega_{[0]}$ . This makes the semigroups into monoids.

**Proof** Let  $\omega_1(x) \in \omega_i^\circ$ . We show that  $\omega_{[0]}$  is an identity element, and that

$$\omega_1(x) \oplus \omega_{[0]} = \omega_{[0]} \oplus \omega_1(x) = \omega_1(x)$$

So let  $\omega_1(x) = \omega_{[\rho(n)]}(x)$ . Then

$$\omega_{[\rho(n)]}(x) \oplus \omega_{[0]} = \omega_{[\rho(n)+0]}(x) = \omega_{[\rho(n)]}(x)$$

On the other hand,

$$\omega_{[0]} \oplus \omega_{[\rho(n)]}(x) = \omega_{[0+\rho(n)]}(x) = \omega_{[\rho(n)]}(x)$$

We are done.  $\omega_i^\circ \cup \omega_{[0]}$  are *monoids*.  $\square$

**Claim 2.47.** (*August 13, 2014*)  $\omega_i^\circ \cup \omega_{[0]}$  form groups.

**Proof** We know that  $\omega_1^\circ \cup \omega_{[0]}$  are *monoids* from **Claim 2.46**. We just need to show the existence of inverses, by showing that an element of  $\omega_1^\circ \cup \omega_{[0]}$  together with its inverse yields the identity as we defined it. So take  $\omega_1(x), \omega_2(x) \in \omega_1^\circ \cup \omega_{[0]}$ , and let  $\omega_1(x) = \omega_{[\rho(n)]}$ . The inverse element is  $\omega_1(x) = \omega_{[-\rho(n)]}$ , since

$$\omega_1(x) \oplus \omega_2(x) = \omega_{[\rho(n)]} \oplus \omega_{[-\rho(n)]} = \omega_{[\rho(n)-\rho(n)]} = \omega_{[0]}$$

□

**Remark 2.15.** (*May 5, 2014*) Notice how the definition takes into account Taylor polynomial coefficients (thus all analytic functions are included) and those that are not (even those that are as yet unclassified), and all sequences which may be scaled by a factor as well.

**Claim 2.48.** (*May 5, 2014*) Let  $f(x)$  is Maclaurin-expandable so that

$$f(x) = \sum_{n=0}^{\infty} \frac{f^n(0)x^n}{n!}$$

Then

$$\sum_{n=0}^{\infty} \frac{f^n(0)}{(n+1)!} = \int_0^1 f(x) dx$$

**Proof**

$$\int_0^1 f(x) dx = \int_0^1 A_i \cdot D dx$$

for some  $i$ th row of  $A$ . Such a row would have to be of form

$$A_i = \left[ f(0) \quad \dots \quad \frac{f^n(0)}{n!(n+1)} \quad \dots \right]$$

Then the integral

$$\int_0^1 A_i \cdot D dx = \sum_j a_{i,j} = \sum_{n=0}^{\infty} \frac{f^n(0)}{n!(n+1)} = \sum_{n=0}^{\infty} \frac{f^n(0)}{(n+1)!}$$

□

**Remark 2.16.** (*May 5, 2014*) Notice that all Maclaurin-expandable functions converge in area (have stable area) in the interval from 0 to 1, a remarkable fact.

**Example 2.6.** (*May 5, 2014*) Take

$$f(x) = e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

By applying **Claim 2.48**, it follows that

$$\sum_{n=0}^{\infty} \frac{1}{(n+1)!} = \int_0^1 e^x dx = e - 1$$

**Remark 2.17.** (*May 5, 2014*) Now we have a happy way to construct (any and all) Pasquali patches which are functions of  $x$  alone, merely by taking a sequence which is convergent at the sum. From a different vantage point, we have a way to describe any and all probability distributions in the interval  $[0, 1]$  merely by specifying a sequence convergent at the sum!

**Remark 2.18.** (*May 5, 2014*) Quantum mechanically, we now know all possible shapes that a stationary (limiting) eigen wavevector can take.

**Remark 2.19.** (*May 5, 2014*) This gives us extraordinary power to calculate convergent sums via integration. It also gives us extraordinary power to express any number as an infinite sum, for example.

## 3. DYNAMICS

## 3.1. Stability and Stationary States.

**Corollary 3.1.** (*April 6, 2013*) *If*

$$\lim_{t \rightarrow \infty} p_t(x, y) = p_\infty(x)$$

*t* ∈ ℤ<sup>+</sup>, *then*

$$\lim_{t \rightarrow \infty} \Delta P^t = 0$$

**Proof** Take

$$\Delta P^t = P^{t+1} - P^t$$

Applying the limit at infinity we get

$$\begin{aligned} \lim_{t \rightarrow \infty} \Delta P^t &= \lim_{t \rightarrow \infty} [P^{t+1} - P^t] \\ &= \lim_{t \rightarrow \infty} P^{t+1} - \lim_{t \rightarrow \infty} P^t \\ &= P^\infty - P^\infty \\ &= 0 \end{aligned}$$

where the next-to-last step is justified by the hypothesis of the corollary (in other words, we assume convergence to  $p_\infty(x)$ ). □

**Corollary 3.2.** (*March 31, 2013*) *If*

$$\lim_{t \rightarrow \infty} c_t(x) = p_\infty(x)$$

*t* ∈ ℤ<sup>+</sup>, *then*

$$\lim_{t \rightarrow \infty} \Delta c_t(x) = 0$$

**Proof 1** From **Claim 2.25**,

$$c_{t+1}(x) = c_0(x) \star P^{t+1}$$

Thus we have that

$$\begin{aligned} c_{t+1}(x) - c_t(x) &= c_0(x) \star P^{t+1} - c_0(x) \star P^t \\ &= c_0(x) \star (P^{t+1} - P^t) \end{aligned}$$

where this part is justified by **Corollary 1.5, Distributive Property of the Star Operator**. Next at steady-state

$$\begin{aligned} \lim_{t \rightarrow \infty} \Delta c_t(x) &= \lim_{t \rightarrow \infty} [c_0(x) \star (P^{t+1} - P^t)] \\ &= c_0(x) \star \left( \left[ \lim_{t \rightarrow \infty} P^{t+1} \right] - \left[ \lim_{t \rightarrow \infty} P^t \right] \right) \\ &= c_0(x) \star (P^\infty - P^\infty) \\ &= c_0(x) \star 0 \\ &= 0 \end{aligned}$$

Where we have pulled the limit under the star operator by using the hypothesis and conclusion of **Corollary 2.27**, **Corollary 3.1**, and we also used **Claim 1.6 Zero Property of the Star Product**. □

**Proof 2** Using the **Claim 2.25** equivalence, we have

$$c_{t+1}(x) = c_t(x) \star P^1$$

and

$$c_{t+1}(x) - c_t(x) = (c_t(x) - c_{t-1}(x)) \star P^1$$

Taking the limit as  $t \rightarrow \infty$  we get:

$$\begin{aligned}
\lim_{t \rightarrow \infty} \Delta c_t(x) &= \lim_{t \rightarrow \infty} (c_t(x) - c_{t-1}(x)) \star P^1 \\
&= \lim_{t \rightarrow \infty} (c_t(x) \star P^1 - c_{t-1}(x) \star P^1) \\
&= \lim_{t \rightarrow \infty} [c_t(x) \star P^1] - \lim_{t \rightarrow \infty} [c_{t-1} \star P^1] \\
&= \left[ \lim_{t \rightarrow \infty} c_t(x) \right] \star P^1 - \left[ \lim_{t \rightarrow \infty} c_{t-1}(x) \right] \star P^1 \\
&= c_\infty(x) \star P^1 - c_\infty(x) \star P^1 \\
&= (c_\infty(x) - c_\infty(x)) \star P^1 \\
&= 0 \star P^1 \\
&= 0
\end{aligned}$$

in which we used the hypothesis and limit implication of **Corollary 2.29**. Here we also used **Claim 1.6 Zero Property of the Star Product**.  $\square$

**Construction 3.1.** (*March 31, 2013*) Let  $k(c(x), t)$  is a piecewise continuous linear functional that is equal to  $c_t(x)$  star-weighted by an arbitrary  $g(y), g: [0, 1] \rightarrow \mathbb{R}$ , in other words,  $c_t(x) \star g(y)$ . Create it so that between each unit time interval the slope is  $\Delta c_t(x)$  for any  $x$ .

**Claim 3.3.** (*March 31, 2013*) If

$$\lim_{t \rightarrow \infty} c_t(x) = p_\infty(x)$$

$t \in \mathbb{R}^+$ , then

$$\lim_{t \rightarrow \infty} \frac{\partial k(c(x), t)}{\partial t} = 0$$

**Proof** For the intervals between  $c_{t+1}(x)$  and  $c_t(x)$ , the derivative is  $\Delta c_t(x)$  by construction. Thus we can take

$$\lim_{t \rightarrow \infty} \frac{\partial k(c(x), t)}{\partial t} = \lim_{t \rightarrow \infty} \Delta c_t(x) = 0$$

by **Claim 3.2**. Note that at infinity, convergence of  $c_t(x)$  eventually smooths any kinks at integer time-steps and allows for the derivative to be defined there.  $\square$

**Remark 3.1.** (*March 31, 2013*) The above claim intends to construct a situation in which probability on a Pasquali patch will accumulate or un-accumulate uniformly (linearly) in each unit of time interval, but stabilizing in the long-run, for each  $x$ .

**Remark 3.2.** (*March 31, 2013*) Anatomically, it seems clear that, because of its recursive dependence,  $c_t(x)$  has basic form:

$$c_t(x) = \overbrace{I(x)}^{\text{invariant in time}} + W(x) \cdot \overbrace{c_{t-1}(x) \star g(y)}^{\text{variable in time}}$$

The idea is to create a “continuous continuation” of  $c_t(x)$  by using  $k(c(x), t)$ .

**Claim 3.4.** (*March 31, 2013*) Take

$$c_t^o(x) = \overbrace{I(x)}^{\text{invariant in time}} + W(x) \cdot \overbrace{k(c(x), t-1)}^{\text{variable in time}}$$

$t \in \mathbb{R}^+$ , with the usual supposition of convergence to  $p_\infty(x)$  of  $c_t(x)$ . Then the partial derivative

$$\lim_{t \rightarrow \infty} \frac{\partial c_t^o(x)}{\partial t} = 0$$

**Proof** By taking the partial derivative in the intervals where it is defined (except at positive integer  $t$  initially, but then for practical purposes the convergence smooths the derivative at these points too), we obtain

$$\begin{aligned}
\lim_{t \rightarrow \infty} \frac{\partial}{\partial t} [I(x) + W(x)k(c(x), t-1)] &= W(x) \lim_{t \rightarrow \infty} \frac{\partial}{\partial t} [k(c(x), t-1)] \\
&= W(x) \cdot 0 \\
&= 0
\end{aligned}$$

where we used **Claim 3.3**.  $\square$

**Remark 3.3.** *The newly created function  $c_t^\circ(x)$  is now continuous in  $t$  and not just defined at integer time-steps. This in essence describes a manner in which to define in-between powers of Pasquali patches. Sometimes it is possible to find  $k(x,t)$  explicitly, as the next example shows. However, although we may guarantee  $c_t(x)$  is a probability distribution at  $t \in \mathbb{Z}^+ \cup \{0\}$ , the uniform accumulation of  $k(c(x), t)$  at in-between times may not sum to 1 in the integral (due to the linear conversion to the next integer value of  $t$ ). This may require a different definition of the accumulation (than linear). However at the limit of time at infinity this is unimportant. In addition, if time is quantized, the continuous description may even be superfluous.*

#### 4. THE PASQUALIAN

**Definition 4.1.** *(August 4, 2014) A Pasqualian is the function  $p(x,y,t)$ , continuous in all variables, which describes at each integer  $t \in \mathbb{Z}^+$  the Pasquali patches of a system. In particular,  $p(x,y,1) = p_1(x,y)$ , the initial Pasquali patch, and  $\lim_{t \rightarrow \infty} p(x,y,t) = p_\infty(x)$ . Since it must be true that the Pasqualian coincides at integer steps with the appropriate star-product-produced-from-a-generator Pasquali patch, we must have that  $\int_0^1 p(x,y,t) dx = u(y) = 1$  is true  $\forall y,t$  are continuous. Furthermore,*

$$\lim_{t \rightarrow \infty} \frac{\partial p(x,y,t)}{\partial t} = 0$$

*In other words, the value of the Paqualian at infinity stabilizes smoothly.*

**Example 4.1.** *(August 4, 2014) Take for example the Pasquali patch  $p_1(x,y) = 1 + \cos(2\pi x) \cos(2\pi y)$  with powers:*

$$\begin{aligned} p_1(x,y) &= 1 + \cos(2\pi x) \cos(2\pi y) \\ p_2(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{2} \\ p_3(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{4} \\ p_4(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{8} \\ p_5(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{16} \\ p_6(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{32} \\ &\vdots \\ p_n(x,y) &= 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{2^{(n-1)}} \end{aligned}$$

*It is clear that the Pasqualian is  $p(x,y,t) = 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{2^{(t-1)}}$ . Notice we could obtain the Pasqualian by an inductive argument, much like in **Example 2.2**, and assuming interpolation at non-integer  $t$ .*

**Remark 4.1.** *(August 4, 2014) Notice that the Pasqualian provides us with immense power to invert the star product transform. Assume the inverse of the generator Pasquali patch exists. If we look at  $t = 2$ , and the corresponding Pasquali patch  $p_2(x,y) = p(x,y,2)$ , for example, the application of the inverse generator Pasquali patch via the Pasqualian would yield  $p(x,y,1)$ . Applying the inverse again we obtain  $p(x,y,0)$ . If we keep applying such, all of the sudden we can keep inverting into the negative powers, by calculating  $p(x,y,t)$  with  $t \in \mathbb{Z}^-$ , something we could not do before with the star product transform. Forward and backward star-product multiplications are translated to sums or subtractions in the variable  $t$  (kind of what the logarithm does for usual multiplications). Finally, we have not only the inverse of the generator, but any integer power, for we can always subtract or sum a number of steps to obtain this first Pasquali patch.*

**Remark 4.2.** *(August 4, 2014) Notice that the Pasqualian provides us with an additional advantage, and that is calculating intermediate Pasquali patches, or Pasquali patches for non-integer values of  $t$ . This is extraordinary in that the procedure essentially defines the process of taking roots on the star-product transform. Because of **Definition 4.1**, such intermediate powers or roots are guaranteed to be Pasquali patches as well.*

**Claim 4.1.** *(August 4, 2014) Not all systems have a Pasqualian.*

**Proof by Counterexample** Take **Example 2.2** which differs from **Example 4.1** by a negative sign. Recall we could, via induction, describe integer *Pasquali patches* by the equation

$$p_n(x, y) = 1 - \frac{\cos(2\pi x) \cos(2\pi y)}{(-2)^{(n-1)}}$$

However we cannot make  $n$  continuous because of the negative sign in front of the 2, and since the equation is therefore defined only at integer  $n$ , a *Pasqualian* does not exist.  $\square$

**Remark 4.3.** (*August 4, 2014*) We emphasize the fact that a *Pasqualian* can be obtained as we did: via inductive examination, by looking at *Pasquali patch sequences* coming from a generator, and then assuming continuity in the step variable to interpolate (although this technique may not produce a *Pasqualian* for all systems, as we have seen in **Claim 4.1**). There are special systems with particular form which we will describe presently.

#### 4.1. Intermediate Form.

**Remark 4.4.** (*August 11, 2014*) We may posit that the intermediate form of the *Pasqualian* is something like  $p(x, y, t) = X(x)Y(y)T(t)$ . However this specification is not adequate, since by **Definition 4.1**  $\int_0^1 p(x, y, t) dx = 1$  should be a constant (equal to 1) and not a function of  $t$ . This simple observation causes us to amend the definition to something like  $p(x, y, t) = M(x, y) \cdot T(t) + C(x, y)$ , because then the function of  $t$  can vanish when we integrate across  $x$ , provided  $M(x, y)$  integrates to zero and  $C(x, y)$  to 1 as the definition requires. We work with this form of the *Pasqualian* and see what insights we can obtain.

4.1.1.  $p(x, y, t) = M(x, y) \cdot T(t) + C(x, y)$ .

Properties of  $T(t)$ .

**Claim 4.2.** (*August 10, 2014*)

$$\lim_{t \rightarrow \infty} T(t) = 0$$

**Proof** By **Definition 4.1** the following holds true:

$$\lim_{t \rightarrow \infty} p(x, y, t) = p_\infty(x)$$

Thus, we have that

$$\lim_{t \rightarrow \infty} (M(x, y) \cdot T(t) + C(x, y)) = M(x, y) \cdot \lim_{t \rightarrow \infty} T(t) + C(x, y) = p_\infty(x)$$

But then  $p_\infty(x)$  is solely a function of  $x$ , so it follows that the time function must vanish at the limit. Thus we conclude  $\lim_{t \rightarrow \infty} T(t) = 0$ . We examine the function  $C(x, y) = C(x) = p_\infty(x)$  more closely presently.  $\square$

**Claim 4.3.** (*August 10, 2014*)

$$\lim_{t \rightarrow \infty} \frac{\partial T(t)}{\partial t} = 0$$

**Proof** Recall from **Definition 4.1** that

$$\lim_{t \rightarrow \infty} \frac{\partial p(x, y, t)}{\partial t} = 0$$

Thus we have that:

$$\lim_{t \rightarrow \infty} \frac{\partial [M(x, y) \cdot T(t) + C(x, y)]}{\partial t} = 0$$

or

$$M(x, y) \cdot \lim_{t \rightarrow \infty} \frac{\partial T(t)}{\partial t} = 0$$

For nonzero  $M(x, y)$ , the result follows.  $\square$

Properties of  $M(x, y)$  and  $C(x, y)$ .

**Claim 4.4.** (*June 4, 2014*) If  $T(t)$  is never zero, then

$$\int_0^1 M(x, y) dx = 0$$

Moreover

$$\int_0^1 C(x, y) dx = 1$$



**Proof** This follows from the fact that, at any time  $t \in \mathbb{R}$  it must be true that the integral of the *Pasqualian* in the  $x$  direction must add up to one (at integer times the *Pasqualian* becomes a *Pasquali patch*, and according to the definition (**Definition 4.1**) such must integrate to 1 in the  $x$  direction). Thus we have that

$$\int_0^1 p(x, y, t) dx = \int_0^1 (M(x, y) \cdot T(t) + C(x, y)) dx = \int_0^1 M(x, y) \cdot T(t) dx + \int_0^1 C(x, y) dx = 1$$

The first integral, that is

$$\int_0^1 M(x, y) \cdot T(t) dx = 0$$

because the time function must vanish, otherwise we have the function add to the total area and such can never be constant or, in particular, 1 (it would have to have a varying time term). This implies

$$\int_0^1 M(x, y) dx = 0$$

provided  $T(t)$  is never zero. But then it must be true that

$$\int_0^1 C(x, y) dx = 1$$

□

**Corollary 4.5.** (*June 4, 2014*)  $C(x, y)$  is a *Pasquali patch*.

**Proof** Since

$$\int_0^1 C(x, y) dx = 1$$

by **Claim 4.4**, it follows from **Definition 2.1** that  $C(x, y)$  is a *Pasquali patch*. □

**Claim 4.6.** (*June 4, 2014*)

$$C(x, y) = C(x) = p_\infty(x)$$

**Proof** This follows from the fact that the *Pasqualian* must stabilize as we take the time limit to infinity. Thus

$$\lim_{t \rightarrow \infty} p(x, y, t) = \lim_{t \rightarrow \infty} [M(x, y) \cdot T(t) + C(x, y)] = C(x, y)$$

by taking the limit, but additionally the *Pasqualian* must stabilize to the stationary surface  $p_\infty(x)$ , and thus  $C(x, y) = p_\infty(x)$  which we know is solely a function of  $x$ . □

Thus we have the new equation of probability evolution:

**Remark 4.5.** (*August 11, 2014*) In summary, the *Pasqualian* can be written as

$$p(x, y, t) = M(x, y) \cdot T(t) + p_\infty(x)$$

with the following properties:

- (1)  $\lim_{t \rightarrow \infty} T(t) = 0$
- (2)  $\lim_{t \rightarrow \infty} \frac{\partial T(t)}{\partial t} = 0$
- (3)  $T(t)$  is never zero
- (4)  $\int_0^1 M(x, y) dx = 0$
- (5)  $C(x, y) = p_\infty(x)$

This shows that we can create an evolving (probability) system that is continuous in time by specifying the stationary surface,  $M(x, y)$ , and the manner by which we will decay to the stationary surface via  $T(t)$ . The stationary surface can be specified using **Claim 2.42**, The Grand Classification Theorem. Also, by using our **Construction 2.1** of *Pasquali patches*, we can exactly specify the form of such  $M(x, y)$  by taking three different functions (so we have 3 degrees of freedom from 4 starting functions). Lastly, it seems clear that  $T(t)$  will have to be of the family

$$\mathbb{T} = \{a \cdot e^{-rt}, a \cdot t^{-n}, \dots\}$$

that are functions asymptotic to  $y = 0$ . We must just make sure that the subsequent *Pasquali patches* that define the system are correctly specified at integer time.

Form of  $M(x,y)$ .

**Claim 4.7.** (June 4, 2014) The specific form of  $M(x, y)$ , using **Construction 2.1**, for a Pasqualian  $p(x, y, t)$  is

$$M(x, y) = \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot (g_1(y) - B) \cdot \frac{1}{T(1)}$$

where  $F_1 = \int_0^1 f_1(x) dx$ ,  $F_2 = \int_0^1 f_2(x) dx$  and  $B$  is given recursively by  $B = p_\infty(x) \star g_1(y)$ . Notice that we solely depend on the fact that  $B$  converges but that this will converge for arbitrary (analytic, polynomial, Taylor-expandable) choices  $f_{1,2}(x)$  and  $g_1(y)$  as shown in **Claim 2.22**.

**Proof** Take the Pasqualian at time  $t = 1$  so that

$$p(x, y, 1) = M(x, y) \cdot T(1) + p_\infty(x)$$

Recall that the first Pasquali patch using **Construction 2.1** is

$$p_1(x, y) = f_1(x)g_1(y) + f_2(x) \frac{(1 - g_1(y)F_1)}{F_2}$$

and that the stationary patch is

$$p_\infty(x) = \frac{f_2(x)}{F_2} - \left( \frac{f_2(x)F_1}{F_2} - f_1(x) \right) B$$

with  $B = p_\infty(x) \star g_1(y)$  by **Claim 2.22**. Thus at time  $t = 1$  we have the following equation:

$$p(x, y, 1) = p_1(x, y)$$

which is

$$M(x, y) \cdot T(1) + p_\infty(x) = f_1(x)g_1(y) + f_2(x) \frac{(1 - g_1(y)F_1)}{F_2}$$

Next we solve for

$$M(x, y) \cdot T(1) = f_1(x)g_1(y) + \frac{f_2(x)}{F_2} - f_2(x)g_1(y) \frac{F_1}{F_2} - \frac{f_2(x)}{F_2} + f_2(x) \frac{F_1}{F_2} B - f_1(x)B$$

Simplifying we get

$$M(x, y) \cdot T(1) = (g_1(y) - B) f_1(x) + \frac{F_1}{F_2} (B - g_1(y)) f_2(x)$$

and factoring we get

$$M(x, y) = \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot (g_1(y) - B) \cdot \frac{1}{T(1)}$$

as we wanted to show.  $\square$

**Remark 4.6.** (June 9, 2014) For **Construction 2.1**, the equation of probability propagation (the Pasqualian) becomes:

$$p(x, y, t) = \overbrace{\left[ \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot (g_1(y) - B) \cdot \frac{1}{T(1)} \right]}^{M(x,y) \cdot T(t)} \cdot T(t) + \overbrace{\left[ \frac{f_2(x)}{F_2} - \left( \frac{f_2(x)F_1}{F_2} - f_1(x) \right) B \right]}^{p_\infty(x)}$$

or put in another form:

$$p(x, y, t) = \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot \left[ g_1(y) \cdot \frac{T(t)}{T(1)} - B \left( \frac{T(t)}{T(1)} - 1 \right) \right] + \frac{f_2(x)}{F_2}$$

Although we could arbitrarily choose  $f_1(x)$ ,  $f_2(x)$  and  $g_1(y)$ , there is additional work to be done with the function  $T(t)$ , we we must make sure to take Pasquali patch powers (other than the generator) and match them to the Pasqualian to get the appropriate rate of decay. Skipping this step, however, makes for an excellent first approximation of the final form the Pasqualian will take.

**Proposition 4.8.** (June 4, 2014) In **Construction 2.1**, there is a particular case where we have the following special relation between functions of  $x$ :  $F_2 \cdot f_1(x) = F_1 \cdot f_2(x)$  or  $f_2(x) = \alpha f_1(x)$  with  $\alpha = \frac{F_2}{F_1}$ .

**Proof** Since by **Claim 4.4** we have that  $\int_0^1 M(x, y) dx = 0$ , it follows that

$$\int_0^1 \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot (g_1(y) - B) dx = 0$$

If the part that is a function of  $y$  is not zero, we must have

$$\int_0^1 \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) dx = F_1 - \frac{F_1}{F_2} F_2 = 0$$

which we have shown that it is indeed the case for any function  $f_1(x)$  and  $f_2(x)$ . Notice that there is a particular instance in which we may have the integral vanish if the part

$$\left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) = 0$$

before we integrate, in which case we have exactly the relationship  $F_2 \cdot f_1(x) = F_1 \cdot f_2(x)$  or  $f_2(x) = \alpha f_1(x)$  where  $\alpha$  is the ratio between the areas of the two functions in the interval from 0 to 1, that is  $\frac{F_2}{F_1}$ .  $\square$

**Corollary 4.9.** (June 4, 2014) For **Construction 2.1**,  $M(x, y) = 0$  if and only if  $f_2(x) = \alpha f_1(x)$  or  $g_1(y) = B$  (or both).

**Proof** We have:

$\Rightarrow$  Since

$$M(x, y) = \left( f_1(x) - \frac{f_2(x)}{\alpha} \right) \cdot (g_1(y) - B) \cdot \frac{1}{T(1)} = 0$$

it follows that either  $\left( f_1(x) - \frac{f_2(x)}{\alpha} \right) = 0$  in which case  $f_2(x) = \alpha f_1(x)$ ; or  $(g_1(y) - B) = 0$  in which case  $g_1(y) = B$ ; or both situations apply.

$\Leftarrow$  On the other hand it can be easily seen from the formula that if  $f_2(x) = \alpha f_1(x)$ , then  $\left( f_1(x) - \frac{f_2(x)}{\alpha} \right) = 0$  which causes  $M(x, y) = 0$ ; if  $g_1(y) = B$  then  $(g_1(y) - B) = 0$  and  $M = 0$ ; and if both situations apply then  $M(x, y) = 0$  because  $0 \cdot 0 = 0$ .  $\square$

**Corollary 4.10.** (June 4, 2014) For **Construction 2.1**,  $M(x, y) = 0$  if and only if the Pasqualian is  $p(x, y, t) = p_\infty(x)$ .

**Proof** We have:

$\Rightarrow$  The Pasqualian  $p(x, y, t) = M(x, y) \cdot T(t) + p_\infty(x)$  becomes  $p(x, y, t) = p_\infty(x)$  with the substitution  $M(x, y) = 0$ .

$\Leftarrow$  Since the Pasqualian is  $p_\infty(x) = M(x, y) \cdot T(t) + p_\infty(x)$ , it follows  $M(x, y) \cdot T(t) = 0$ . But  $T(t)$  is never zero (see **Remark 4.5**) so it must be true that  $M(x, y) = 0$ .  $\square$

**Corollary 4.11.** (June 4, 2014) In **Construction 2.1**, the Pasqualian  $p(x, y, t) = p_\infty(x)$  if and only if  $f_2(x) = \alpha f_1(x)$  or  $g_1(y) = B$  (or both).

**Proof** This follows from **Corollary 4.9** and **Corollary 4.10**.  $\square$

**Remark 4.7.** This works out nicely for us in the sense that, for  $f_2(x) = \alpha f_1(x)$ , the Pasqualian is independent of time (and the  $y$  variable). See **Remark 7.1** about time freezing and time-evolution. Thus imposing a single restriction on our choice of functions of  $x$  for **Construction 2.1** works out the Pasqualian to be a single function of  $x$  for all time.

**Corollary 4.12.** (June 4, 2014) For **Construction 2.1**, if  $f_2(x) = \alpha f_1(x)$ , then

$$p(x, y, t) = p_\infty(x) = \frac{f_1(x)}{F_1} = \frac{f_1(x)}{\int_0^1 f_1(x) dx}$$

**Proof** Since for **Construction 2.1**,

$$p_\infty(x) = \frac{f_2(x)}{F_2} - \left( \frac{f_2(x)}{\alpha} - f_1(x) \right) B$$

and  $f_2(x) = \alpha f_1(x)$ , we have that

$$p_\infty(x) = \frac{\alpha f_1(x)}{F_2} - (0)B = \frac{f_1(x)}{F_1}$$

upon substitution. □

**Example 4.2.** (*August 11, 2014*) Take **Example 4.1** with Pasqualian

$$p(x, y, t) = 1 + \frac{\cos(2\pi x) \cos(2\pi y)}{2^{t-1}}$$

and  $x, y \in [0, 1], t \in \mathbb{R}$ . Anatomically,

$$p(x, y, t) = \overbrace{\cos(2\pi x) \cos(2\pi y)}^{M(x, y)} \cdot \overbrace{\frac{1}{2^{t-1}}}^{T(t)} + \overbrace{1}^{p_\infty(x)}$$

Notice how all functions conform to the specifications in **Remark 4.5**. In particular, let  $f_1(x) = \cos(2\pi x), g_1(y) = \cos(2\pi y)$ , and  $f_2(x) = 1$ . Using **Remark 4.6**,

$$p(x, y, t) = \left( f_1(x) - \frac{F_1}{F_2} f_2(x) \right) \cdot \left[ g_1(y) \cdot \frac{T(t)}{T(1)} - B \left( \frac{T(t)}{T(1)} - 1 \right) \right] + \frac{f_2(x)}{F_2}$$

matches exactly:

$$p(x, y, t) = \left( \cos(2\pi x) - \frac{0}{1} \cdot 1 \right) \cdot \left[ \cos(2\pi y) \cdot \frac{T(t)}{T(1)} - 0 \cdot \left( \frac{T(t)}{T(1)} - 1 \right) \right] + \frac{1}{1}$$

where we are left only to determine  $T(t)$  by matching Pasquali patches using the star-product transform. Thus the above simplifies to

$$p(x, y, t) = \cos(2\pi x) \cos(2\pi y) \cdot \frac{T(t)}{T(1)} + 1$$

We may know by performing a star-product transform on the original Pasquali patch (that is,  $p(x, y, 1)$ ) that

$$p(x, y, 2) = \cos(2\pi x) \cos(2\pi y) \cdot \frac{T(2)}{T(1)} + 1 = \cos(2\pi x) \cos(2\pi y) \cdot \frac{1}{2} + 1$$

Thus we have that  $T(2) = \frac{T(1)}{2}$ . Knowledge that

$$p(x, y, 3) = \cos(2\pi x) \cos(2\pi y) \cdot \frac{1}{4} + 1$$

gives that  $T(3) = \frac{T(1)}{4}$ . Thus we deduce the relationship that  $T(2) = 2 \cdot T(3)$ . We may posit that  $T(t) = a \cdot e^{-r \cdot t}$  for some  $a, r \in \mathbb{R}$ . Substituting we have  $a \cdot e^{-2r} = 2 \cdot a \cdot e^{-3r}$  and  $e^r = 2$  with  $r = \ln(2)$ . Thus  $T(t)$  takes the form  $a \cdot 2^{-t}$  and coefficient comparison (using  $T(1)$ ) gives  $a = 2$ . Finally  $T(t) = 2 \cdot 2^{-t}$  and

$$p(x, y, t) = \cos(2\pi x) \cos(2\pi y) \cdot \frac{1}{2^{t-1}} + 1$$

as we wanted to show, without inducing. We remark that we need knowledge of three Pasquali patches since this allows us to create two equations for two unknowns,  $a$  and  $r$ .

#### 4.2. General Form.

**Remark 4.8.** (*August 11, 2014*) We may posit a more general form of the Pasqualian  $p(x, y, t)$ . Let  $M_i, C: [0, 1]^2 \rightarrow \mathbb{R}$  and  $T_i: \mathbb{R} \rightarrow \mathbb{R}$ . We can define the Pasqualian by:

$$p(x, y, t) = M_1(x, y) \cdot T_1(t) + M_2(x, y) \cdot T_2(t) + \dots + M_k(x, y) \cdot T_k(t) + \dots + C(x, y)$$

or, to put it differently

$$p(x, y, t) = \sum_{k=1}^n M_k(x, y) \cdot T_k(t) + C(x, y) = \mathbf{M}(x, y) \cdot \mathbf{T}(t) + C(x, y)$$

Finally, because all claims we derived in the previous section apply, including all specifications for each of the functions, it follows that the general form is then

$$p(x, y, t) = \mathbf{M}(x, y) \cdot \mathbf{T}(t) + p_\infty(x)$$

with

$$(1) \lim_{t \rightarrow \infty} \mathbf{T}(t) = 0$$

- (2)  $\lim_{t \rightarrow \infty} \frac{\partial \mathbf{T}(t)}{\partial t} = 0$
- (3)  $\mathbf{T}(t)$  is never zero
- (4)  $\int_0^1 \mathbf{M}(x, y) dx = 0$
- (5)  $C(x, y) = p_\infty(x)$

5. QUANTUM MECHANICS / IN PROGRESS

5.1. **Propagating the Probability Distribution Wavevector: The Pasqualian.** Let us now examine how the probability distribution  $c_t^\circ(x)$  changes in time.

**Claim 5.1.** (June 9, 2013) A continuous-in-time Pasquali patch  $p(x, y, t)$  (a Pasqualian), so that

$$\lim_{t \rightarrow \infty} \frac{\partial P^t}{\partial t} = 0$$

and for which

$$\frac{\partial c_t^\circ(x)}{\partial t} = -c_t(x) \star M$$

$M$  is a function of  $x, y$ , has form

$$p(x, y, t) = M \cdot e^{-t} + C(x, y)$$

**Proof (May 19, 2013)** Recall the expression from **Proof 1** of **Claim 3.2**, where we have:

$$c_{t+1}(x) - c_t(x) = c_0(x) \star (P^{t+1} - P^t)$$

which we now write

$$\Delta c_t(x) = c_0(x) \star \Delta P^t$$

The continuous time analogue is:

$$\frac{\partial c_t^\circ(x)}{\partial t} = c_0(x) \star \frac{\partial P^t}{\partial t}$$

Now let us rewrite  $c_t^\circ(x)$  as  $\psi(x, t)$  to make explicit the connection to quantum mechanics. Thus we have

$$\frac{\partial \psi(x, t)}{\partial t} = \psi(x, 0) \star \frac{\partial P^t}{\partial t}$$

In BraKet notation the connection is absolutely clear (minus the complex variables), we have:

$$\frac{\partial \langle \psi(x, t) |}{\partial t} = \langle \psi(x, 0) | \frac{\partial P^t}{\partial t}$$

In the Shrödinger time-dependent picture,

$$\frac{\partial \langle \psi(x, t) |}{\partial t} = \langle \psi(x, t) | M$$

that is, the state wavevector (in this case a probability distribution) time derivative is proportional to the state wavevector (also a probability distribution by **Claim 2.10**) itself (typically, the wavefunction  $M$  is static and not changing in time, though this may not be the case). Now recall that by **Claim 2.25** (in BraKet notation and continuous time)

$$\langle \psi(x, t) | = \langle \psi(x, 0) | P^t$$

Putting these last three equations together, we get

$$\langle \psi(x, 0) | \frac{\partial P^t}{\partial t} = \langle \psi(x, t) | M = \langle \psi(x, 0) | P^t M$$

which we can simplify as

$$\frac{\partial P^t}{\partial t} = P^t M$$

and solves  $P^t$  as an exponential

$$p(x, y, t) = M \cdot e^t + C(x, y)$$

(this is the Shrödinger solution of the wavefunction!). In order for the solution to have stationary states, however, we have to require that the time derivative actually be asymptotic to 0 (see **Corollary 2.21**). Thus we must really have

$$p(x, y, t) = M \cdot e^{-t} + C(x, y)$$

which implies in turn by reverse argument that

$$\frac{\partial \langle \psi(x, t) |}{\partial t} = - \langle \psi(x, t) | M$$

In particular, then, now we are aligned with **Corollary 3.1** for continuous time. We may rename the *Pasquali patch* a *Pasqualian*, in line with the subject-matter nomenclature (Hamiltonian, e.g.).  $\square$

**Remark 5.1** (Wave-Particle Duality: Resolving the Paradox). (*May 19, 2013*) *We can see now that the Pasqualian pushes the original wavevector  $\langle \psi(x, 0) |$ , really a probability distribution, forward in time. But the Pasqualian wavefunction describes the probability of transition from a (certain) state to another (certain) state at any point in time. In fact, it tells us how the proportions (number of photons) accumulate in space through time. Thus, under this light, the wave interpretation of wave-particle duality arises from a consideration of probability (number of photon) accumulations. The fact is that photons (electrons, or other particles) do not interfere in the ordinary sense of the word (much less singly) with themselves... it is their stacked accumulations that follows the natural probability/frequency law. Photons (electrons, etc.) seem perfectly corpuscular, their wave-like behavior arising from transition-probability dynamics. In this interpretation, waves arise simply from summing position probabilities of particles. Thus we resolve the wave-particle duality by thinking of a photon (electron, etc.) not as possessing both wave and particle properties, but by understanding the interference pattern as aggregate accumulations of many particles as they interact in time following the natural aggregation law. That is, under this interpretation the understanding is that a photon (electron, etc.) is a full particle which, in conjunction with many others, together bundle and spread this way and that along the space of the system according to the laws of probability (the law of step-wise accumulation). This notion we shall call Particle Singularity for purposes of contrast.*

**Remark 5.2** (Reinterpretation of the Least Action Principle for the Path of a Particle). (*May 19, 2013*) *Using the Pasqualian, we can reinterpret the least action principle by stating that a particle will follow the path that maximizes the position probability along the totality of (probability) wavevectors of the system (plus minus perturbations).*

## 6. APPLICATIONS

**Example 6.1.** (*May 5, 2013*) *Suppose we have an idealized canal of width 1, on which a fluid flow has been established in some remote past. Let us focus solely on the dynamics of the surface. Pick a spot along the canal which we will call  $t_0$ . Next pick a spot  $y_0 \in [0, 1]$  along the width of the canal, which we will monitor. Pick a second spot  $t_1$  down the canal, some distance from the original spot we picked. Now let us assume that, up the canal at some remote point, a paper boat has been released. We will only care about the boat if the boat passes through  $(t_0, y_0)$  which we have picked, and we will write down the resultant position at  $t_1$ . Let us do this a number of times with any number of boats, and obtain a distribution of the position of the boat at  $t_1$ , saving it. Next let us repeat the experiment, this time focusing on  $y_0'$ , save the resultant distribution at  $t_1$ , and so on and so forth, until we are comfortable having mapped the totality of positions at  $t_0$ . Let us next put together (stack, respecting the natural order of  $y$ ) all the distributions we obtained at  $t_1$ . We now have a discrete surface which we can smooth to obtain a Pasquali patch.*

*Let us now look at position  $t_2$  which is the same distance as  $t_1$  is from  $t_0$ . Having defined the dynamics of the system (from a single Pasquali patch), the dynamics at  $t_2$  can be theoretically described by  $P^2$ . We can therefore ascertain the probability that we will find the boat at  $t_2$  along the width of the canal. In fact, at  $t_n$ ,  $n$  very large, we can ascertain the probability that the boat will be at any position along the width. It should be close to  $P^\infty$ . More importantly, a great distance from the origin (any distance, not necessarily a distance  $n \cdot \Delta t_n$ ), the position probability is aptly described by  $P^\infty$ . See **Figure 9** and **Figure 10**.*

*This simple thought experiment brings about several questions. What if the dynamics of the surface system are described by the Pasquali patch, but at points which are not a distance  $\Delta t_n$  apart? In other words, what if the description is apt but at points that are not linear in distance? This curious situation suggests a time anomaly, and therefore a manner in which we can measure time warps (by measuring the actual time differences between Pasquali patches). See **Figure 11**.*

*Next, we looked at the surface dynamics of the system. If we add a depth variable to the canal, we can in theory produce a Pasquali cube, which would measure the dynamics of any point on the  $[0, 1] \times [0, 1]$  cross-section a discrete distance down the canal (and any distance very far from our origin).*

*A third question arises when we consider the same canal, but whose width opens by a scalar (linear) amount a distance from our chosen origin. There is no reason we cannot “renormalize” the width (set it equal to 1 again) at a point some set distance from our chosen origin, and proceed with our analysis as before. See **Figure 12**.*

*A fourth question arises when we begin to think that the canal width does not open (or close) linearly.*

7. REMARKS THAT CHALLENGE ESTABLISHED NOTIONS

**Remark 7.1. (January 13, 2014)** *The statistical description of a dynamical system (as one described by a generator Pasquali patch) really does give us a lot of power in computing the probable position of a particle (photon, electron) moving in space at different (integer) time intervals. If the quantum mechanical supposition of time having a minimum discreteness (Planck-time) is correct, we can find the finest Pasquali patch generator that will give a complete description of the dynamical system. Any Pasquali patch generator descriptive of the system which is not this first will generate an accurate, yet less refined (coarser) version of the system (this is what we mean by **Claim 1.13**, in that such Pasquali patch will be contained in the finest description, yet is not the finest), and in fact either system of course converges to the same steady state (this is what is meant by **Claim 2.31**). If we are able to find a continuous description (like the Shrödinger equation, via a Pasqualian) of such system then we are in luck (this description would be the finest, though non-discrete, description), and I speculate though I cannot be sure yet that either discrete descriptions will be contained in such.*

*Whatever the description of the dynamical system via a generator Pasquali patch (or a Pasqualian), each Pasquali patch represents the transition (position) probabilities of a particle (photon, electron) moving within that system. If we suppose that the particle moves with same velocity (take photons in vacuum as an example), then each Pasquali patch power is descriptive of the transition-position probability at equally spaced spacial or distance intervals. Though I've remarked about this before, if it were the case that, for a particle with a particular (steady) velocity, the Pasquali patch power is not exactly equally spaced in distance intervals, it must mean that the arrow of time is bent (time is moving faster for smaller-spaced intervals, slower for longer-spaced). We have not yet described accelerating particles but at present that is not of our interest.*

*However, we can tell if time is passing so long as each Pasquali patch description is different at each (equal or unequal) interval. If a single Pasquali patch were to describe the system at EACH distance interval, there is no way to know if time is moving at all. Take for example **Claim 2.32**. We had the collection  $\mathbb{Q} = \{Q^1, Q^2, \dots, Q^k, \dots\}_{k \in \mathbb{Z}^+}$  with  $Q = q(x, y)$  being an explicit function of  $y$  and converging to  $Q^\infty = 1$ . We could track the time-distance interval via the Pasquali patch power, so that 1 was the first distance interval from start (we take it as given that time is not being bent, so that a fixed distance implies the passage of 1 unit of time), 2 was the second distance interval (2 units of time), and so on, and we could tell if time were bent if each power were descriptive of different distance intervals. Furthermore, since each  $Q \in \mathbb{Q}$  is different, this implies each position transition probability is different and the system is in movement.*

*This is definitely not the case with the collection  $\mathbb{P} = \{P^1 = 1, P^2 = 1, \dots, P^j, \dots\}_{j \in \mathbb{Z}^+}$  which also converges to  $P^\infty = 1$ . Since at each distance interval the movement probability is the same (uniform), one cannot be convinced that each power represents a distance interval equal to equally spaced time intervals or different-spaced time intervals. Where we could with  $\mathbb{Q}$  ascertain that time was moving, we cannot with  $\mathbb{P}$ . The statistical description cannot tell if the system is frozen.*

*When a system has reached the steady state (which, is the highest entropy state! See **Corollary 2.21**), there is no way to tell if time flows, as the statistical description is and forever will be unchanging. Recall that the steady state for a Pasquali patch is always a function of  $x$  alone, say  $p(x)$ . Furthermore recall that any power of  $p(x)$  is always  $p(x)$  itself (see **Claim 2.8**). We reach an impasse: is time flowing normally, faster than what is conventional, slower? At such a point it is impossible to say, at least from the statistical point of view. We would have to track particles individually in order to ascertain if they have deviated their path at all (it could be the case that they shifted to all positions with equal probability or in the shape of  $p(x)$ , e.g., but we cannot be sure of either situation).*

8. RELEVANT GENERALIZATIONS

8.1. **The Eigenvalue Question.** Consider the general eigenvalue question

$$j(x) \star h(x, y) = \lambda j(x)$$

for general (well-behaved) functions  $j: [0, 1] \rightarrow \mathbb{R}$  and  $h: [0, 1]^2 \rightarrow \mathbb{R}$ .

**Claim 8.1. (July 24, 2013)** *If  $\lambda$  is an eigenvalue of  $h(x, y)$ , then  $\lambda^n$  is an eigenvalue of  $h_n(x, y)$ , the  $n$ th power of  $h(x, y)$ ,  $n \in \mathbb{Z}^+$ .*

**Proof by Induction** Let

$$j(x) \star h(x, y) = \lambda j(x)$$

Suppose that

$$j(x) \star h_k(x, y) = \lambda^k j(x)$$

Then

$$\begin{aligned}
j(x) \star h_{k+1}(x, y) &= (j(x) \star h_k(x, y)) \star h(x, y) \\
&= \left( \lambda^k j(x) \right) \star h(x, y) \\
&= \lambda^k (j(x) \star h(x, y)) \\
&= \lambda^k \cdot \lambda \cdot j(x) \\
&= \lambda^{k+1} j(x)
\end{aligned}$$

We have made liberal use of **Claim 1.8 Associativity of the Star Product**.  $\square$

**Corollary 8.2.** (*July 24, 2013*) This is a restatement of **Corollary 2.13** for Pasquali patches. Provided we can find  $a(x)$  so that it is fixed under the Pasquali patch  $p(x, y)$ , that is,

$$a(x) \star p(x, y) = a(x)$$

and  $\lambda = 1$ , it follows that  $\lambda = 1$  for all  $p_n(x, y)$ ,  $n \in \mathbb{Z}^+$ .

**Proof** Simply apply **Claim 8.1** to the fact that *Pasquali patches* have  $\lambda = 1$  eigenvalue (provided  $a(x)$  exists).  $\square$

## 8.2. Surface Trace or *str*.

**Definition 8.1.** (*March 3, 2013*) Take the function  $h: [0, 1]^2 \rightarrow \mathbb{R}$ . Let the surface trace be the value of the integral of the diagonal  $y = -x + 1$  or  $x = 1 - y$  of such surface. In other words, it is:

$$\text{str}[h(x, y)] = \int_0^1 h(x, 1 - x) dx = \int_0^1 h(1 - y, y) dy$$

## 8.3. Specific Finite-Dot-Product Surfaces.

**Definition 8.2.** (*March 3, 2013*) A specific finite-dot-product surface is a function  $h: [0, 1]^2 \rightarrow \mathbb{R}$  such that:

$$h(x, y) = \sum_{k=1}^n f_k(x)g_k(y) = \mathbf{f}(x) \cdot \mathbf{g}(y)$$

8.3.1. *Specific Finite-Dot-Product Surface Trace (str).*

**Claim 8.3.** (*March 3, 2013*) The specific finite-dot-product surface trace is:

$$\text{str}[h(x, y)] = \sum_{k=1}^n C_{k,k} = \text{tr} \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,n} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n,1} & C_{n,2} & \cdots & C_{n,n} \end{bmatrix}$$

where  $C_{k,k} = f_k(x) \star g_k(x)$ .

**Proof by Induction** We have:

$$\text{str}[h(x, y)] = \int_0^1 h(x, 1 - x) dx = \int_0^1 h(1 - y, y) dy$$

by **Definition 8.1**. We can think of the specific finite-dot-product surface

$$h(x, y) = f_1(x)g_1(y)$$

and readily calculate the trace *str* in this way:

$$\begin{aligned}
\text{str}[h(x, y)] &= \int_0^1 h(1 - y, y) dy = \int_0^1 f_1(1 - y)g_1(y) dy \\
&= \int_0^1 f_1(1 - y)g_1(y) dy \\
&= f_1(x) \star g_1(y) \\
&= C_{1,1} \\
&= \text{tr}[C_{1,1}]
\end{aligned}$$



This constitutes the base case. So assume that the  $m$ th case is true, and

$$\begin{aligned} \text{str}[h(x, y)] &= \sum_{k=1}^m C_{k,k} = \text{tr} \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,m} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m,1} & C_{m,2} & \cdots & C_{m,m} \end{bmatrix} \\ &= \sum_{k=1}^m \left( \int_0^1 f_k(1-y)g_k(y) dy \right) \\ &= \int_0^1 \left( \sum_{k=1}^m f_k(1-y)g_k(y) \right) dy \end{aligned}$$

We now show that the  $m+1$  case works as well. So let

$$h(x, y) = \sum_{k=1}^{m+1} f_k(x)g_k(y) = \sum_{k=1}^m f_k(x)g_k(y) + f_{m+1}(x)g_{m+1}(y)$$

Then the surface trace can be calculated as

$$\begin{aligned} \text{str}[h(x, y)] &= \int_0^1 h(1-y, y) dy = \int_0^1 \left( \sum_{k=1}^m f_k(1-y)g_k(y) + f_{m+1}(1-y)g_{m+1}(y) \right) dy \\ &= \int_0^1 \left( \sum_{k=1}^m f_k(1-y)g_k(y) \right) dy + \int_0^1 f_{m+1}(1-y)g_{m+1}(y) dy \\ &= \sum_{k=1}^m C_{k,k} + C_{m+1,m+1} \\ &= \sum_{k=1}^{m+1} C_{k,k} \\ &= \text{tr} \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,m} & C_{1,m+1} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,m} & C_{2,m+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{m,1} & C_{m,2} & \cdots & C_{m,m} & C_{m,m+1} \\ C_{m+1,1} & C_{m+1,2} & \cdots & C_{m+1,m} & C_{m+1,m+1} \end{bmatrix} \end{aligned}$$

□

### 8.3.2. Specific Finite-Dot-Product Surface Eigenvalues.

**Claim 8.4.** (*March 25, 2011*) Let  $e: [0, 1] \rightarrow \mathbb{R}$  be smooth and well-behaved, and  $h(x, y) = f_1(x)g_1(y) + f_2(x)g_2(y)$  with  $h: [0, 1]^2 \rightarrow \mathbb{R}$  likewise. Then there are **two**  $\lambda$  values that satisfy

$$e(x) \star h(x, y) = \lambda e(x)$$

provided

$$C_{1,1} = f_1(x) \star g_1(y)$$

$$C_{1,2} = f_1(x) \star g_2(y)$$

$$C_{2,1} = f_2(x) \star g_1(y)$$

$$C_{2,2} = f_2(x) \star g_2(y)$$

converge.

**Proof** In **Claim 8.4**, the equation

$$e(x) \star h(x, y) = \lambda e(x)$$

can be written out specifically as

$$\int_0^1 e(1-y)h(x, y) dy = \lambda e(x)$$

More explicitly, this is:

$$\begin{aligned}\lambda e(x) &= \int_0^1 e(1-y)(f_1(x)g_1(y) + f_2(x)g_2(y)) dy \\ &= f_1(x) \int_0^1 e(1-y)g_1(y) dy + f_2(x) \int_0^1 e(1-y)g_2(y) dy \\ &= B_1 f_1(x) + B_2 f_2(x)\end{aligned}$$

where  $B_1, B_2$  are constants. If we divide by  $\lambda$  as

$$e(x) = \frac{B_1}{\lambda} f_1(x) + \frac{B_2}{\lambda} f_2(x)$$

then the equation must hold provided  $\lambda \neq 0$ . So we have excluded an eigenvalue right from the start.

We can systematically write the derivatives of  $e(x)$ :

$$\begin{aligned}e(x) &= \frac{B_1}{\lambda} f_1(x) + \frac{B_2}{\lambda} f_2(x) \\ e'(x) &= \frac{B_1}{\lambda} f_1'(x) + \frac{B_2}{\lambda} f_2'(x) \\ e''(x) &= \frac{B_1}{\lambda} f_1''(x) + \frac{B_2}{\lambda} f_2''(x) \\ &\vdots \\ e^k(x) &= \frac{B_1}{\lambda} f_1^k(x) + \frac{B_2}{\lambda} f_2^k(x) \\ &\vdots\end{aligned}$$

again with  $\lambda \neq 0$ . We want to calculate the constants  $B_1, B_2$ , to see if they are restricted in some way by a formula, and we do this by integrating by parts as we did before. Thus, we have that if

$$B_1 = \int_0^1 e(1-y)g_1(y) dy$$

the tabular method gives:

Derivatives	Integrals
$e(1-y)$	$g_1(y)$
$-e'(1-y)$	$G_1^1(y)$
$e''(1-y)$	$G_1^2(y)$
$\vdots$	$\vdots$

and so,

$$\begin{aligned}B_1 &= \int_0^1 e(1-y)g_1(y) dy \\ &= e(1-y)G_1^1(y)|_0^1 + e'(1-y)G_1^2(y)|_0^1 + \dots \\ &= \sum_{i=0}^{\infty} e^i(1-y)G_1^{i+1}(y) \Big|_0^1\end{aligned}$$

if we remember the alternating sign of the multiplications, and we are allowed some leeway in notation. Ultimately, this last bit means:  $\sum_{i=0}^{\infty} e^i(0)G_1^{i+1}(1) - \sum_{i=0}^{\infty} e^i(1)G_1^{i+1}(0)$ . Since we have already explicitly written the derivatives of  $e(x)$ , the  $e^i(0), e^i(1)$  derivatives can be written as

$$\frac{B_1}{\lambda} f_1^i(0) + \frac{B_2}{\lambda} f_2^i(0)$$

and

$$\frac{B_1}{\lambda} f_1^i(1) + \frac{B_2}{\lambda} f_2^i(1)$$

respectively. We have then:

$$B_1 = \sum_{i=0}^{\infty} \left( \frac{B_1}{\lambda} f_1^i(0) + \frac{B_2}{\lambda} f_2^i(0) \right) G_1^{i+1}(1) - \sum_{i=0}^{\infty} \left( \frac{B_1}{\lambda} f_1^i(1) + \frac{B_2}{\lambda} f_2^i(1) \right) G_1^{i+1}(0)$$

Since we aim to solve for  $B_1$ , multiplying by  $\lambda$  makes things easier, and also we must rearrange all elements with  $B_1$  in them, so we get:

$$\lambda B_1 = B_1 \sum_{i=0}^{\infty} \left( f_1^i(0)G_1^{i+1}(1) - f_1^i(1)G_1^{i+1}(0) \right) + B_2 \sum_{i=0}^{\infty} \left( f_2^i(0)G_1^{i+1}(1) - f_2^i(1)G_1^{i+1}(0) \right)$$

Subtracting both sides the common term and factoring the constant we endeavor to solve for, we get:

$$\left( \lambda - \sum_{i=0}^{\infty} \left( f_1^i(0)G_1^{i+1}(1) - f_1^i(1)G_1^{i+1}(0) \right) \right) B_1 = B_2 \sum_{i=0}^{\infty} \left( f_2^i(0)G_1^{i+1}(1) - f_2^i(1)G_1^{i+1}(0) \right)$$

or

$$B_1 = \frac{B_2 \sum_{i=0}^{\infty} f_2^i(1-y)G_1^{i+1}(y) \Big|_0^1}{\lambda - \sum_{i=0}^{\infty} f_1^i(1-y)G_1^{i+1}(y) \Big|_0^1} = \frac{B_2 (f_2(x) \star g_1(y))}{\lambda - (f_1(x) \star g_1(y))} = \frac{B_2 C_{2,1}}{\lambda - C_{1,1}}$$

A similar argument for  $B_2$  suggests

$$B_2 = \frac{B_1 \sum_{i=0}^{\infty} f_1^i(1-y)G_2^{i+1}(y) \Big|_0^1}{\lambda - \sum_{i=0}^{\infty} f_2^i(1-y)G_2^{i+1}(y) \Big|_0^1} = \frac{B_1 (f_1(x) \star g_2(y))}{\lambda - (f_2(x) \star g_2(y))} = \frac{B_1 C_{1,2}}{\lambda - C_{2,2}}$$

where the new constants introduced emphasizes the expectation that the sums (or integrals) converge. Plugging in the one into the other we get:

$$B_1 = \frac{\left( \frac{B_1 C_{1,2}}{\lambda - C_{2,2}} \right) C_{2,1}}{\lambda - C_{1,1}} = \frac{B_1 C_{1,2} C_{2,1}}{(\lambda - C_{2,2})(\lambda - C_{1,1})}$$

and now we have additional restrictions on lambda:  $\lambda \neq C_{2,2}$  and  $\lambda \neq C_{1,1}$ . Furthermore, the constant  $B_1$  drops out of the equation, suggesting these constants can be anything we can imagine (all of  $\mathbb{R}$  without restriction), but then we have the constraint:

$$(\lambda - C_{2,2})(\lambda - C_{1,1}) = C_{1,2} C_{2,1}$$

(Notice how this equation can be put in determinant form!

$$\det \begin{vmatrix} C_{1,1} - \lambda & C_{1,2} \\ C_{2,1} & C_{2,2} - \lambda \end{vmatrix} = 0$$

This form of the equation becomes the basis of **Claim 8.6.**)

Expanding the equation suggests:

$$\lambda^2 - (C_{2,2} + C_{1,1})\lambda + (C_{1,1}C_{2,2} - C_{1,2}C_{2,1}) = 0$$

which we can solve by the quadratic equation of course, as:

$$\lambda_{1,2} = \frac{(C_{2,2} + C_{1,1}) \pm \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2}$$

So not only is  $\lambda$  not equal to many values, it is incredibly restricted to two of them.

Now the constants  $C_{1,1}, C_{1,2}, C_{2,1}, C_{2,2}$  have been expressed in terms of the integration-by-parts sums in the expectation that subsequent derivatives of  $f_{1,2}(x)$  will eventually vanish (or are periodically 0<sup>1</sup>). There is nothing to stop us from redefining them in terms of  $g_{1,2}(y)$  derivatives instead, if these were to vanish quicker or were to force the sum convergence where the derivatives of  $f_{1,2}(x)$  did not.<sup>2</sup>

Now, figuring out the eigenfunctions  $e(x)$  that go together with these eigenvalues is an exercise in finding constants  $B_1$  and  $B_2$  for a given eigenvalue.<sup>3</sup> □

\*\*\*\*\*begin in-progress\*\*\*\*\*

<sup>1</sup>Need to clarify

<sup>2</sup>For this reason it may be convenient to leave the integration-by-parts method open-ended by rewriting and redefining shorthand

$$\begin{aligned} f_1(x) \star g_1(y) &= C_{1,1} \\ f_2(x) \star g_1(y) &= C_{2,1} \\ f_1(x) \star g_2(y) &= C_{1,2} \\ f_2(x) \star g_2(y) &= C_{2,2} \end{aligned}$$

like we did.

<sup>3</sup>Need to show

**Claim 8.5.** (January 26, 2013) Pasquali patches constructed as by **Construction 2.1** always have a  $\lambda = 1$  eigenvalue.

[In progress ] □

\*\*\*\*\*end in-progress\*\*\*\*\*

**Claim 8.6.** (January 26, 2013) The allowable values of  $\lambda$  is equal to the number of (pair) function terms

$$h(x, y) = \sum_{k=1}^n f_k(x)g_k(y)$$

has, provided pairwise star products between functions of  $x$  and functions of  $y$  converge. In particular, these can be found by

$$\det |A - \lambda I| = 0$$

where  $A$  is an  $n \times n$  matrix of pairwise star products  $f_i(x) \star g_j(y)$  (we call such constants  $C_{i,j}$ ) with  $i, j \in \{1 \dots n\}$ , and  $I$  is the identity matrix. This creates a characteristic equation, in direct analogy to how we obtain eigenvalues in linear algebra contexts.

**Proof** The base case has already been shown in **Claim 8.4**. Suppose that

$$h(x, y) = f_1(x)g_1(y) + f_2(x)g_2(y) + \dots + f_k(x)g_k(y)$$

and as before, we are looking for

$$e(x) \star h(x, y) = \lambda e(x)$$

Arguing similarly as in **Claim 8.4**, we end up with the linear system:

$$\lambda B_1 = B_1 C_{1,1} + B_2 C_{2,1} + \dots + B_k C_{k,1}$$

$$\lambda B_2 = B_1 C_{1,2} + B_2 C_{2,2} + \dots + B_k C_{k,2}$$

⋮

$$\lambda B_k = B_1 C_{1,k} + B_2 C_{2,k} + \dots + B_k C_{k,k}$$

for which we can write the augmented matrix

$$\left[ \begin{array}{cccc|c} C_{1,1} - \lambda & C_{2,1} & \dots & C_{k,1} & 0 \\ C_{1,2} & C_{2,2} - \lambda & \dots & C_{k,2} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{1,k} & C_{2,k} & \dots & C_{k,k} - \lambda & 0 \end{array} \right]$$

Now the determinant of the square matrix must be equal to 0, otherwise there is exactly one solution for constants  $B_1, B_2, \dots, B_k$  (we are specifically looking that these constants be *any* value, so the matrix must be singular and consequently the determinant equal to zero). Thus we have that

$$\det \begin{vmatrix} C_{1,1} - \lambda & C_{2,1} & \dots & C_{k,1} \\ C_{1,2} & C_{2,2} - \lambda & \dots & C_{k,2} \\ \vdots & \vdots & \ddots & \vdots \\ C_{1,k} & C_{2,k} & \dots & C_{k,k} - \lambda \end{vmatrix} = 0$$

The  $k + 1$ th case can be argued similarly. With

$$h(x, y) = f_1(x)g_1(y) + f_2(x)g_2(y) + \dots + f_k(x)g_k(y) + f_{k+1}(x)g_{k+1}(y)$$

we get:

$$\lambda B_1 = B_1 C_{1,1} + B_2 C_{2,1} + \dots + B_k C_{k,1}$$

$$\lambda B_2 = B_1 C_{1,2} + B_2 C_{2,2} + \dots + B_k C_{k,2}$$

⋮

$$\lambda B_k = B_1 C_{1,k} + B_2 C_{2,k} + \dots + B_k C_{k,k}$$

$$\lambda B_{k+1} = B_1 C_{1,k+1} + B_2 C_{2,k+1} + \dots + B_{k+1} C_{k+1,k+1}$$

and so we endeavor to solve the augmented matrix:

$$\left[ \begin{array}{cccccc|c} C_{1,1} - \lambda & C_{2,1} & \dots & C_{k,1} & C_{k+1,1} & 0 \\ C_{1,2} & C_{2,2} - \lambda & \dots & C_{k,2} & C_{k+1,2} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ C_{1,k} & C_{2,k} & \dots & C_{k,k} - \lambda & C_{k+1,k} & 0 \\ C_{1,k+1} & C_{2,k+1} & \dots & C_{k,k+1} & C_{k+1,k+1} - \lambda & 0 \end{array} \right]$$

so that the vector  $B_1, B_2, \dots, B_k, B_{k+1}$  admits an infinity of solutions. We are thus again looking for the singular matrix with determinant zero:

$$\det \begin{vmatrix} C_{1,1} - \lambda & C_{2,1} & \dots & C_{k,1} & C_{k+1,1} \\ C_{1,2} & C_{2,2} - \lambda & \dots & C_{k,2} & C_{k+1,2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{1,k} & C_{2,k} & \dots & C_{k,k} - \lambda & C_{k+1,k} \\ C_{1,k+1} & C_{2,k+1} & \dots & C_{k,k+1} & C_{k+1,k+1} - \lambda \end{vmatrix} = 0$$

which we can now simplify to

$$\det |A - \lambda I| = 0$$

as we wanted. □

### 8.3.3. Functions on Eigenvalues of Specific Finite-Dot-Product Surfaces.

*sdet.*

**Definition 8.3** (Specific Finite-Dot-Product Surface Determinant or *sdet*). (*February 10, 2013*) Specifically in a linear-algebra context, the determinant of a square matrix is the product of its eigenvalues. When we talk about the specific finite-dot-product surface

$$h(x, y) = \sum_{k=1}^n f_k(x)g_k(y)$$

we shall **define** the surface determinant or *sdet* as the product of the eigenvalues it generates:

$$\text{sdet } |h(x, y)| = \prod_{k=1}^n \lambda_k$$

**Claim 8.7.** (*February 10, 2013*) The *sdet* for

$$h(x, y) = f_1(x)g_1(y) + f_2(x)g_2(y)$$

is

$$\text{sdet } |h(x, y)| = C_{1,1}C_{2,2} - C_{1,2}C_{2,1} = \det \begin{vmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{vmatrix}$$

**Proof** This follows directly from the eigenvalue formulation:

$$\lambda_{1,2} = \frac{(C_{2,2} + C_{1,1}) \pm \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2}$$

The product is:

$$\begin{aligned} \lambda_1 \cdot \lambda_2 &= \left( \frac{(C_{2,2} + C_{1,1}) + \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2} \right) \cdot \left( \frac{(C_{2,2} + C_{1,1}) - \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2} \right) \\ &= \frac{(C_{2,2} + C_{1,1})^2 - (C_{2,2} - C_{1,1})^2 - 4C_{1,2}C_{2,1}}{4} \\ &= \frac{4C_{1,1}C_{2,2} - 4C_{1,2}C_{2,1}}{4} \\ &= C_{1,1}C_{2,2} - C_{1,2}C_{2,1} \\ &= \det \begin{vmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{vmatrix} \end{aligned}$$

□

**Conjecture 8.1.** (February 23, 2013) The sdet of a specific finite surface with  $n$  pair functions of  $x$  and  $y$  terms is:

$$\text{sdet } |h(x, y)| = \det \begin{vmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,n} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n,1} & C_{n,2} & \cdots & C_{n,n} \end{vmatrix}$$

str (Revisited).

**Claim 8.8.** (March 3, 2013) In the context of specific finite-dot-product surfaces,

$$\text{str } [h(x, y)] = \sum_{k=1}^n \lambda_k$$

**Proof by Induction** From the eigenvalue formulation of **Claim 8.4**, we have

$$\lambda_{1,2} = \frac{(C_{2,2} + C_{1,1}) \pm \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2}$$

The sum is:

$$\begin{aligned} \lambda_1 + \lambda_2 &= \left( \frac{(C_{2,2} + C_{1,1}) + \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2} \right) + \left( \frac{(C_{2,2} + C_{1,1}) - \sqrt{(C_{2,2} - C_{1,1})^2 + 4C_{1,2}C_{2,1}}}{2} \right) \\ &= C_{1,1} + C_{2,2} \end{aligned}$$

which is exactly  $\text{str } [f_1(x)g_1(y) + f_2(x)g_2(y)]$ . This constitutes the base case. Next assume that it is true that

$$\text{str } \left[ \sum_{k=1}^m f_k(x)g_k(y) \right] = \sum_{k=1}^m C_{k,k} = \sum_{k=1}^m \lambda_k$$

Then

$$\begin{aligned} \text{str } \left[ \sum_{k=1}^{m+1} f_k(x)g_k(x) \right] &= \sum_{k=1}^{m-1} C_{k,k} + C_{m,m} + C_{m+1,m+1} \\ &= \end{aligned}$$

□

\*\*\*\*\*end in-progress\*\*\*\*\*

**8.4. Specific Infinite-Dot-Product Surfaces.**

**Remark 8.1.** (February 23, 2013) There is no reason why we should restrict ourselves to the study of specific finite-dot-product surfaces, where we could make the leap to specific infinite-dot-product surfaces of the form

$$h(x, y) = \sum_{k=0}^{\infty} f_k(x)g_k(y)$$

**Conjecture 8.2.** (February 23, 2013) Conjecture ?? suggests that the str of a specific infinite-dot-product surface is:

$$\text{str } [h(x, y)] = \sum_{k=1}^{\infty} \lambda_k = \sum_{k=1}^{\infty} C_{k,k}$$

provided all  $C_{k,k}$  converge in their calculation and the sum itself converges.

**8.5. Specific Finite-Dot-Product Surface Specific Infinite-Dot-Product Representations.**

**Example 8.1.** (February 23, 2013) Recall the Maclaurin series expansion

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

We can think of this equation as

$$\underbrace{f_1^{\circ}(x)}_{e^x} \cdot \underbrace{g_1^{\circ}(y)}_1 = \underbrace{f_1(x)}_1 \cdot \underbrace{g_1(y)}_1 + \underbrace{f_2(x)}_x \cdot \underbrace{g_2(y)}_1 + \underbrace{f_3(x)}_{\frac{x^2}{2!}} \cdot \underbrace{g_3(y)}_1 + \underbrace{f_4(x)}_{\frac{x^3}{3!}} \cdot \underbrace{g_4(y)}_1 + \cdots$$

In other words, a specific finite-dot-product surface on the LHS and a specific infinite-dot-product surface on the RHS. The LHS has sum of eigenvalues (eigenvalue)

$$e^x \star 1 = \int_0^1 e^{(1-y)} dy = e - 1$$

by the trivial case of **Claim 8.6**, and the RHS is calculated directly by

$$\begin{aligned} &= \int_0^1 \left( \sum_{k=0}^{\infty} \frac{(1-y)^k}{k!} \right) dy \\ &= \sum_{k=0}^{\infty} \left( \int_0^1 \frac{(1-y)^k}{k!} dy \right) \\ &= \sum_{k=0}^{\infty} \left( - \frac{(1-y)^{(k+1)}}{(k+1)k!} \Big|_0^1 \right) \\ &= \sum_{k=0}^{\infty} \frac{1}{(k+1)!} \\ &= \sum_{k=1}^{\infty} \frac{1}{k!} \end{aligned}$$

where we have pulled the integral inside the sum due to absolute convergence and the infinite sum of factorial reciprocals therefore of course also converges.<sup>4</sup> This gives credence to **Conjecture 8.2**, since the second row is exactly the str of a specific infinite-dot-product surface

$$\text{str} \left| \sum_{k=0}^{\infty} \frac{x^k}{k!} \right| = 1 \star 1 + x \star 1 + \frac{x^2}{2!} \star 1 + \frac{x^3}{3!} \star 1 + \dots = \sum_{k=1}^{\infty} \lambda_k$$

**Claim 8.9.** (February 23, 2013) Take the Taylor-expandable function  $f(x)$ ,  $f: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$

$$f(x) = \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} (x-a)^i$$

with  $a \in [0, 1]$ . Then its eigenvalue is the convergent series sum

$$\lambda = \sum_{i=0}^{\infty} f^i(a) \cdot \left( \frac{(1-a)^{i+1} - (-a)^{i+1}}{(i+1)!} \right)$$

with  $a \in [0, 1]$ .

**Proof** We have that

$$\underbrace{f_1^\circ(x)}_{f(x)} \cdot \underbrace{g_1^\circ(y)}_1 = \overbrace{\left( \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} (x-a)^i \right)}^{f_1^\circ(x)} \cdot \underbrace{g_1^\circ(y)}_1$$

So then the LHS eigenvalue can be calculated by the trivial case of **Claim 8.6**, and the RHS can be calculated by direct application of star operator

$$\lambda = \left( \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} (x-a)^i \right) \star 1$$

---

<sup>4</sup>One easily checks that the LHS and the RHS are indeed equivalent

$$e - 1 = \sum_{k=1}^{\infty} \frac{1}{k!}$$

by noticing that the Maclaurin expansion of  $e^x$  evaluated at  $x = 1$  yields

$$e = 1 + \sum_{k=1}^{\infty} \frac{1}{k!}$$

If we believe **Conjecture 8.2**, this RHS can be interpreted as the sum-of-eigenvalues of a specific infinite-dot-product surface.

We therefore have

$$\lambda = \int_0^1 \left( \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} (1-y-a)^i \right) dy$$

by definition. By absolute convergence of the sum, we can bring in the integral and solve:

$$\begin{aligned} &= \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} \left( \int_0^1 (1-y-a)^i dy \right) \\ &= \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} \left( \frac{-(1-y-a)^{i+1}}{i+1} \Big|_0^1 \right) \\ &= \sum_{i=0}^{\infty} \frac{f^i(a)}{i!} \left( \frac{(1-a)^{i+1} - (-a)^{i+1}}{i+1} \right) \\ &= \sum_{i=0}^{\infty} f^i(a) \cdot \left( \frac{(1-a)^{i+1} - (-a)^{i+1}}{(i+1)!} \right) \end{aligned}$$

with  $a \in [0, 1]$ . □

**Corollary 8.10.** (*February 23, 2013*) The Maclaurin-expandable  $f(x)$ ,  $f: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$

$$f(x) = \sum_{i=0}^{\infty} \frac{f^i(0)}{i!} x^i$$

has eigenvalue

$$\lambda = \sum_{i=0}^{\infty} \frac{f^i(0)}{(i+1)!}$$

**Proof** We have that by **Claim 8.9**, the Taylor-expandable  $f(x)$  has eigenvalue

$$\lambda = \sum_{i=0}^{\infty} f^i(a) \cdot \left( \frac{(1-a)^{i+1} - (-a)^{i+1}}{(i+1)!} \right)$$

with  $a \in [0, 1]$ . Letting  $a = 0$ , we get

$$\begin{aligned} \lambda &= \sum_{i=0}^{\infty} f^i(0) \cdot \left( \frac{(1)^{i+1} - (0)^{i+1}}{(i+1)!} \right) \\ &= \sum_{i=0}^{\infty} \frac{f^i(0)}{(i+1)!} \end{aligned}$$

□

**Corollary 8.11.** (*February 25, 2013*) The Taylor-expansion of  $f(x)$ ,  $f: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$  about  $a = 1$  has eigenvalue

$$\lambda = \sum_{i=0}^{\infty} \frac{(-1)^i f^i(1)}{(i+1)!} = \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} - \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!}$$

**Proof** This follows directly from **Claim 8.9**, with  $f(x)$  has eigenvalue

$$\lambda = \sum_{i=0}^{\infty} f^i(a) \cdot \left( \frac{(1-a)^{i+1} - (-a)^{i+1}}{(i+1)!} \right)$$



At  $a = 1$ , this becomes

$$\begin{aligned} \lambda &= \sum_{i=0}^{\infty} f^i(1) \cdot \left( \frac{(0)^{i+1} - (-1)^{i+1}}{(i+1)!} \right) \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i f^i(1)}{(i+1)!} \\ &= \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} - \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} \end{aligned}$$

□

**Claim 8.12.** (February 25, 2013) For any (infinitely-differentiable, Taylor-expandable) function  $f(x)$ ,  $f: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$ ,

$$\sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} = \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1) - f^i(0)}{(i+1)!}$$

**Proof** Since both **Corollary 8.10** and **Corollary 8.11** are equal to the specific finite-surface eigenvalue, we have the following:

$$\begin{aligned} \sum_{i=0}^{\infty} \frac{f^i(0)}{(i+1)!} &= \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} - \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} \\ \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(0)}{(i+1)!} + \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(0)}{(i+1)!} &= \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} - \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1)}{(i+1)!} \\ \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} &= \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1) - f^i(0)}{(i+1)!} \end{aligned}$$

□

**Remark 8.2.** (February 25, 2013) It's rather neat that **Claim 8.12** relates the even and odd derivatives of functions, essentially stating that they are constrained in a very specific way at two particular points.

**Example 8.2.** (February 26, 2013) Take for example the rather unassuming function  $f(x) = (x+1)^2$ ,  $f: [0, 1]^2 \rightarrow \mathbb{R}$ . We have:

$$\begin{array}{lll} f(x) = (x+1)^2 & f(1) = 4 & f(0) = 1 \\ f'(x) = 2(x+1) & f'(1) = 4 & f'(0) = 2 \\ f''(x) = 2 & f''(1) = 2 & f''(0) = 2 \\ f'''(x) = 0 & f'''(1) = 0 & f'''(0) = 0 \\ \vdots & \vdots & \vdots \end{array}$$

Let's calculate the odd part as in the LHS of **Claim 8.12**:

$$\sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} = \frac{4+2}{2!} = 3$$

The even part is:

$$\sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1) - f^i(0)}{(i+1)!} = \frac{4-1}{1!} + \frac{2-2}{3!} = 3$$

And the eigenvalue that gave rise to this invariant is:

$$\lambda = \sum_{i=0}^{\infty} \frac{f^i(0)}{(i+1)!} = \frac{1}{1!} + \frac{2}{2!} + \frac{2}{3!} = 1 + 1 + \frac{1}{3} = 7/3$$

**Claim 8.13.** (*April 14, 2013*) Let

$$s^o(n) = \sum_{i=1}^n \frac{1}{(2i)!}$$

and

$$s^e(n) = \sum_{i=0}^n \frac{1}{(2i+1)!}$$

Then

$$\lim_{n \rightarrow \infty} \frac{s^e(n)}{s^o(n)} = \frac{e+1}{e-1} \approx 2.164$$

In other words, the infinite sum  $\lim_{n \rightarrow \infty} s^e(n)$  is approximately 116% larger than the infinite sum  $\lim_{n \rightarrow \infty} s^o(n)$ .

**Proof** Another rather interesting example analogous to **Example 8.2** is the function  $f(x) = e^x$ , with  $f: [0, 1]^2 \rightarrow \mathbb{R}$ . Here since  $f^i(x) = e^x, \forall i \in \mathbb{Z}^+ \cup \{0\}$ , we readily evaluate  $f^i(1) = e$  and  $f^i(0) = 1$  for all non-negative  $i$ . Thus we get:

$$\begin{aligned} \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} &= \frac{e+1}{2!} + \frac{e+1}{4!} + \dots \\ &= (e+1) \cdot \left( \frac{1}{2!} + \frac{1}{4!} + \dots \right) \end{aligned}$$

and

$$\begin{aligned} \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{f^i(1) - f^i(0)}{(i+1)!} &= \frac{e-1}{1!} + \frac{e-1}{3!} + \dots \\ &= (e-1) \cdot \left( \frac{1}{1!} + \frac{1}{3!} + \dots \right) \end{aligned}$$

Since these two equations must be equal by **Claim 8.12**, we get

$$\frac{e+1}{e-1} = \frac{\left(\frac{1}{1!} + \frac{1}{3!} + \dots\right)}{\left(\frac{1}{2!} + \frac{1}{4!} + \dots\right)} = \frac{\sum_{i=0}^{\infty} \frac{1}{(2i+1)!}}{\sum_{i=1}^{\infty} \frac{1}{(2i)!}} = \frac{\lim_{n \rightarrow \infty} s^e(n)}{\lim_{n \rightarrow \infty} s^o(n)} = \lim_{n \rightarrow \infty} \frac{s^e(n)}{s^o(n)}$$

□

**Claim 8.14.** (*April 14, 2013*) The eigenvalue for the function  $f(x) = e^x$ , with  $f: [0, 1]^2 \rightarrow \mathbb{R}$ , is

$$\lambda_{e^x} = e - 1$$

**Proof** Since, by **Claim 8.10**, we have

$$\lambda_{e^x} = \sum_{i=0}^{\infty} \frac{f^i(0)}{(i+1)!}$$

and  $f^i(0) = 1$  for all non-negative  $i$ , the substitution yields:

$$\lambda = \sum_{i=0}^{\infty} \frac{1}{(i+1)!} = \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \dots$$

Next, notice that the Maclaurin expansion of  $e^x$ :

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

evaluated at  $x = 1$  yields

$$e = 1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \dots$$

Thus, we get that

$$e - 1 = 1 + \frac{1}{2!} + \frac{1}{3!} + \dots = \lambda_{e^x}$$

and we are done. □

**Claim 8.15.** (*April 14, 2013*) Another expression for  $\lambda_{e^x}$  is

$$\lambda_{e^x} = \lim_{n \rightarrow \infty} (s^o(n) + s^e(n)) = \lim_{n \rightarrow \infty} s^o(n) + \lim_{n \rightarrow \infty} s^e(n)$$

**Proof** Since

$$\lambda_{e^x} = e - 1 = 1 + \frac{1}{2!} + \frac{1}{3!} + \dots$$

and

$$\lim_{n \rightarrow \infty} s^o(n) = \sum_{i=1}^{\infty} \frac{1}{(2i)!} = \frac{1}{2!} + \frac{1}{4!} + \dots$$

and

$$\lim_{n \rightarrow \infty} s^e(n) = \sum_{i=0}^{\infty} \frac{1}{(2i+1)!} = 1 + \frac{1}{3!} + \frac{1}{5!} + \dots$$

we can easily see that

$$\lim_{n \rightarrow \infty} s^e(n) + \lim_{n \rightarrow \infty} s^o(n) = 1 + \frac{1}{2!} + \frac{1}{3!} + \dots = \lambda_{e^x}$$

as we wanted to show. Thus we have that

$$\lim_{n \rightarrow \infty} s^e(n) + \lim_{n \rightarrow \infty} s^o(n) = e - 1$$

□

**Corollary 8.16.** (April 14, 2013) *The infinite sum*

$$\lim_{n \rightarrow \infty} s^o(n) = \sum_{i=1}^{\infty} \frac{1}{(2i)!} = \frac{(e-1)^2}{2e}$$

*On the other hand the infinite sum*

$$\lim_{n \rightarrow \infty} s^e(n) = \sum_{i=0}^{\infty} \frac{1}{(2i+1)!} = \frac{e^2 - 1}{2e}$$

*Thus, both infinite sums are convergent.*

**Proof 1** We have that

$$\lim_{n \rightarrow \infty} s^o(n) + \lim_{n \rightarrow \infty} s^e(n) = e - 1$$

by **Claim 8.15**. Next, using the ratio

$$\frac{\lim_{n \rightarrow \infty} s^e(n)}{\lim_{n \rightarrow \infty} s^o(n)} = \frac{e+1}{e-1}$$

from **Claim 8.13**, we get that

$$\lim_{n \rightarrow \infty} s^e(n) = \frac{e+1}{e-1} \cdot \lim_{n \rightarrow \infty} s^o(n)$$

Thus it must be true that

$$\lim_{n \rightarrow \infty} s^o(n) + \frac{e+1}{e-1} \cdot \lim_{n \rightarrow \infty} s^o(n) = \left(1 + \frac{e+1}{e-1}\right) \lim_{n \rightarrow \infty} s^o(n) = e - 1$$

which, through direct algebraic manipulation yields:

$$\lim_{n \rightarrow \infty} s^o(n) = \frac{e-1}{1 + \frac{e+1}{e-1}} = \frac{(e-1) \cdot (e-1)}{\left(1 + \frac{e+1}{e-1}\right) \cdot (e-1)} = \frac{(e-1)^2}{2e}$$

Next,

$$\begin{aligned} \lim_{n \rightarrow \infty} s^e(n) &= e - 1 - \lim_{n \rightarrow \infty} s^o(n) = e - 1 - \frac{(e-1)^2}{2e} \\ &= \frac{2e^2 - 2e - (e^2 - 2e + 1)}{2e} \\ &= \frac{e^2 - 1}{2e} \end{aligned}$$

□

**Proof 2** We can use the Maclaurin expansions of

$$\sinh(x) = \sum_{i=0}^{\infty} \frac{x^{2n+1}}{(2n+1)!}$$

and

$$\cosh(x) = \sum_{i=0}^{\infty} \frac{x^{2n}}{(2n)!}$$

evaluated at  $x = 1$ . Therefore we have

$$\cosh(1) = \sum_{i=0}^{\infty} \frac{1}{(2i)!} = \frac{e^2 + 1}{2e}$$

Thus

$$\sum_{i=1}^{\infty} \frac{1}{(2i)!} = \frac{e^2 + 1}{2e} - 1 = \frac{e^2 + 1}{2e} - \frac{2e}{2e} = \frac{(e-1)^2}{2e}$$

On the other hand we have:

$$\sinh(1) = \sum_{i=0}^{\infty} \frac{1}{(2i+1)!} = \frac{e^2 - 1}{2e}$$

□

**Claim 8.17.** (*February 26, 2013*) For any (infinitely-differentiable, Taylor-expandable) function  $f(x)$ ,  $f: [0, 1] \times [0, 1] \rightarrow \mathbb{R}$ ,

$$\sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} = \int_0^1 \left( \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(x)}{i!} \right) dx$$

**Proof** An alternate form of **Claim 8.12** follows from shifting the sum indices:

$$\sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(1) + f^i(0)}{(i+1)!} = \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^{i+1}(1) - f^{i+1}(0)}{i!}$$

The RHS is, in essence:

$$\begin{aligned} &= \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{\int_0^1 f^i(x) dx}{i!} \\ &= \int_0^1 \left( \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{f^i(x)}{i!} \right) dx \end{aligned}$$

where this last step follows from the fact that sums of subsequences must converge (the odd subsequence), thus allowing us to bring out the integral. □

**Claim 8.18.** (*March 14, 2013*) The finite polynomial function  $f: [0, 1]^2 \rightarrow \mathbb{R}$

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0$$

has eigenvalue

$$\lambda = \sum_{i=0}^n \frac{a_i}{i+1}$$

**Proof by Induction** Take

$$f(x) = a_0$$

with  $a_0$  is a constant. The eigenvalue is

$$\lambda = f(x) \star 1 = \int_0^1 a_0 dy = a_0$$

which, using the formula, is

$$\lambda = \sum_{i=0}^0 \frac{a_i}{i+1} = \frac{a_0}{1}$$

and the equivalence is established for the base case. Let's assume the formula works in the  $k$ th case. We show the  $k+1$ th case. So take

$$f(x) = a_{k+1}x^{k+1} + a_kx^k + \dots + a_1x + a_0$$

Which has eigenvalue

$$\begin{aligned} \lambda &= f(x) \star 1 = \int_0^1 \left( a_{k+1}(1-y)^{k+1} + a_k(1-y)^k + \dots + a_1(1-y) + a_0 \right) dy \\ &= \int_0^1 a_{k+1}(1-y)^{k+1} dy + \sum_{i=0}^k \frac{a_i}{i+1} \\ &= \left. \frac{-a_{k+1}(1-y)^{k+2}}{k+2} \right|_0^1 + \sum_{i=0}^k \frac{a_i}{i+1} \\ &= \frac{a_{k+1}}{k+2} + \sum_{i=0}^k \frac{a_i}{i+1} \\ &= \sum_{i=0}^{k+1} \frac{a_i}{i+1} \end{aligned}$$

□

**Corollary 8.19.** (March 14, 2013) For finite polynomial functions,

$$\sum_{i=0}^n \frac{f^i(0)}{(i+1)!} = \sum_{i=0}^n \frac{a_i}{i+1} = \sum_{i=0}^n \frac{(-1)^i f^i(1)}{(i+1)!}$$

**Proof** This is a consequence of **Claim 8.10**, **Claim 8.11**, and **Claim 8.18**.

**Remark 8.3.** *Corollary 8.19 essentially relates the constant (last) derivative of each term of a finite polynomial function with the coefficients of such function, and also the (sum of) coefficients of each derivative to the coefficients of the original function.*

**Claim 8.20.** (March 14, 2013) The eigenvalue for the function  $f: [0, 1]^2 \rightarrow \mathbb{R}$ ,  $f(x) = a \sin(bx + c)$  for constants  $a, b, c$  is

$$\lambda_{f(x)} = \frac{a}{b} (\cos(c) - \cos(b+c))$$

In particular, if  $b \in \{(2m+1)\pi\}_{m \in \mathbb{Z}}$  and  $c \in \{2\pi n\}_{n \in \mathbb{Z}}$

$$\lambda_{f(x)} = \frac{2a}{(2m+1)\pi}$$

The eigenvalue for the function  $g: [0, 1]^2 \rightarrow \mathbb{R}$ ,  $g(x) = a \cos(bx + c)$  is

$$\lambda_{g(x)} = \frac{a}{b} (\sin(b+c) - \sin(c))$$

If  $b, c \in \{\pi n\}_{n \in \mathbb{Z}}$ , then

$$\lambda_{g(x)} = 0$$

**Proof** For  $f(x)$ , the eigenvalue is

$$\begin{aligned} \lambda_{f(x)} &= f(x) \star 1 = a \int_0^1 \sin(b(1-y) + c) dy \\ &= a \left( \frac{\cos(b(1-y) + c)}{b} \right) \Big|_0^1 \\ &= \frac{a}{b} (\cos(c) - \cos(b+c)) \end{aligned}$$

Choosing  $b \in \{(2m+1)\pi\}_{m \in \mathbb{Z}}$  and  $c \in \{2\pi n\}_{n \in \mathbb{Z}}$  yields

$$\lambda_{f(x)} = \frac{a}{(2m+1)\pi} (1+1) = \frac{2a}{(2m+1)\pi}$$

Next, take  $g(x)$  with eigenvalue

$$\begin{aligned} \lambda_{g(x)} &= g(x) \star 1 = a \int_0^1 \cos(b(1-y) + c) dy \\ &= a \left( \frac{\sin(b(1-y) + c)}{-b} \right) \Big|_0^1 \\ &= \frac{a}{b} (\sin(b+c) - \sin(c)) \end{aligned}$$

It is easy to see that with  $b, c \in \{\pi n\}_{n \in \mathbb{Z}}$  we have

$$\lambda_{g(x)} = \frac{a}{b} (0+0) = 0$$

**Corollary 8.21.** (*March 16, 2013*)

$$\sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i+1}}{(2i+1)!} = \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i+1}}{(2i+1)!}$$

with  $n \in \mathbb{Z}$ .

**Proof** Using the Maclaurin expansion of  $\cos(\pi n x + \pi n)$ ,  $n \in \mathbb{Z}$  (notice  $a = 1, b = \pi n, c = \pi n$ ), we get:

$$\cos(\pi n x + \pi n) = \sum_{i=0}^{\infty} \frac{(-1)^i (\pi n x + \pi n)^{2i}}{(2i)!}$$

and eigenvalue, by **Claim 8.20**,

$$\begin{aligned} 0 &= \int_0^1 \left( \sum_{i=0}^{\infty} \frac{(-1)^i (\pi n(1-y) + \pi n)^{2i}}{(2i)!} \right) dy \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i}{(2i)!} \int_0^1 (\pi n(1-y) + \pi n)^{2i} dy \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i}{(2i)!} \left( -\frac{(\pi n(1-y) + \pi n)^{2i+1}}{\pi n(2i+1)} \right) \Big|_0^1 \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i}{(2i)!} \left( \frac{-(\pi n)^{2i+1} + (2\pi n)^{2i+1}}{\pi n(2i+1)} \right) \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i (\pi n)^{2i}}{(2i+1)!} \\ 0 &= \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i}}{(2i+1)!} - \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i}}{(2i+1)!} \\ \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i}}{(2i+1)!} &= \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i}}{(2i+1)!} \\ \sum_{\substack{i \text{ even} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i+1}}{(2i+1)!} &= \sum_{\substack{i \text{ odd} \\ 0 \leq i \leq \infty}} \frac{(\pi n)^{2i+1}}{(2i+1)!} \end{aligned}$$

□

**Claim 8.22.** (*April 6, 2013*) *The Bernoulli polynomials*

$$B_n(x) = \sum_{i=0}^n \binom{n}{i} b_{n-i} x^i$$

with  $B_n : [0, 1]^2 \rightarrow \mathbb{R}$  and  $b_m$  are the Bernoulli numbers, have eigenvalue

$$\lambda_{B_n}(x) = \sum_{i=0}^n \binom{n}{i} \frac{b_{n-i}}{i+1}$$

**Proof** Begin with

$$\begin{aligned} \lambda_{B_n}(x) &= B_n(x) \star 1 \\ &= \int_0^1 B_n(1-y) dy \\ &= \int_0^1 \sum_{i=1}^n \binom{n}{i} b_{n-i} (1-y)^i dy \\ &= \sum_{i=1}^n \binom{n}{i} b_{n-i} \int_0^1 (1-y)^i dy \\ &= \sum_{i=1}^n \binom{n}{i} b_{n-i} \left. \frac{-(1-y)^{i+1}}{i+1} \right|_0^1 \\ &= \sum_{i=0}^n \binom{n}{i} \frac{b_{n-i}}{i+1} \end{aligned}$$

□

**Claim 8.23.** (April 14, 2013)

$$\lambda_{B_n}(x) = 0$$

for  $n \in \mathbb{Z}^+$  with  $b_1 = -\frac{1}{2}$ . Notice the explicit exclusion when  $n = 0$ .

**Proof** First, for  $n$  is odd, we have

$$\int_0^{\frac{1}{2}} \sum_{i=0}^n \binom{n}{i} b_{n-i} x^i dx = - \int_{\frac{1}{2}}^1 \sum_{i=0}^n \binom{n}{i} b_{n-i} x^i dx$$

This is equal to

$$\begin{aligned} \sum_{i=0}^n \binom{n}{i} b_{n-i} \int_0^{\frac{1}{2}} x^i dx &= - \sum_{i=0}^n \binom{n}{i} b_{n-i} \int_{\frac{1}{2}}^1 x^i dx \\ \sum_{i=0}^n \binom{n}{i} b_{n-i} \left. \frac{x^{i+1}}{i+1} \right|_0^{\frac{1}{2}} &= - \sum_{i=0}^n \binom{n}{i} b_{n-i} \left. \frac{x^{i+1}}{i+1} \right|_{\frac{1}{2}}^1 \\ \sum_{i=0}^n \binom{n}{i} b_{n-i} \frac{(\frac{1}{2})^{i+1}}{i+1} &= - \sum_{i=0}^n \binom{n}{i} b_{n-i} \frac{1}{i+1} + \sum_{i=0}^n \binom{n}{i} b_{n-i} \frac{(\frac{1}{2})^{i+1}}{i+1} \\ \sum_{i=0}^n \binom{n}{i} \frac{b_{n-i}}{i+1} &= 0 \end{aligned}$$

Next, if  $n$  is even,  $n \neq 0$ ,

□

**Claim 8.24.** (April 16, 2013) Bernoulli polynomials plus one,  $n > 0$ , are Pasquali patches:

$$B_n(x) + 1 = p^n(x)$$

## 9. EQUIVALENCIES OF THE STAR OPERATOR

### 10. OTHER CLAIMS AND PROOFS

10.1. **Combinatorics.** The following identity arose in my studies of the Mexican lottery.

**Claim 10.1** (Elisa and Carlos Pasquali Combinatorial Identity). (December 27, 2008)

$$\binom{n-s}{r-s} \cdot \binom{n}{s} = \binom{n}{r} \cdot \binom{r}{s}$$

with  $n \geq r \geq s \geq 0$

**Proof** By the definition of the choice operation,

$$\begin{aligned}
\binom{n-s}{r-s} \cdot \binom{n}{s} &= \frac{(n-s)!}{(r-s)!(n-r)!} \cdot \frac{n!}{s!(n-s)!} \\
&= \frac{n!}{(r-s)!(n-r)!s!} \\
&= \frac{n!r!}{r!(n-r)!s!(r-s)!} \\
&= \frac{n!}{r!(n-r)!} \cdot \frac{r!}{s!(r-s)!} \\
&= \binom{n}{r} \cdot \binom{r}{s}
\end{aligned}$$

□

**10.2. Markov Matrices.** The following claim arose due to my studies of Voting Theory and the Schulze method.

**Claim 10.2. (March 2, 2011)** A  $(n+p) \times (n+p)$  Markov matrix  $M = \begin{bmatrix} 0 & A \\ B & 0 \end{bmatrix}$ , so that the upper left zero matrix is  $n \times n$ ,  $A$  is  $n \times p$ ,  $B$  is  $p \times n$  and has the property that every entry is  $\frac{1}{n}$ , and the lower zero matrix is  $p \times p$ :

- (1) Has powers that are Markov matrices
- (2) Has positive even powers that are the same
- (3) Has positive odd powers that are the same, except possibly the first power

**Proof** We have:

- (1) Let  $M, N$  be  $q \times q$  Markov matrices, so that

$$M = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,q} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,q} \\ \vdots & \vdots & \ddots & \vdots \\ a_{q,1} & a_{q,2} & \cdots & a_{q,q} \end{bmatrix}$$

$$N = \begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,q} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,q} \\ \vdots & \vdots & \ddots & \vdots \\ b_{q,1} & b_{q,2} & \cdots & b_{q,q} \end{bmatrix}$$

Then

$$M \cdot N = \begin{bmatrix} \sum_{j=1}^q a_{1,j} b_{j,1} & \sum_{j=1}^q a_{1,j} b_{j,2} & \cdots & \sum_{j=1}^q a_{1,j} b_{j,q} \\ \sum_{j=1}^q a_{2,j} b_{j,1} & \sum_{j=1}^q a_{2,j} b_{j,2} & \cdots & \sum_{j=1}^q a_{2,j} b_{j,q} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{j=1}^q a_{q,j} b_{j,1} & \sum_{j=1}^q a_{q,j} b_{j,2} & \cdots & \sum_{j=1}^q a_{q,j} b_{j,q} \end{bmatrix}$$

If we sum each row we have the vector

$$= \begin{bmatrix} \sum_{k=1}^q \sum_{j=1}^q a_{1,j} b_{j,k} \\ \sum_{k=1}^q \sum_{j=1}^q a_{2,j} b_{j,k} \\ \vdots \\ \sum_{k=1}^q \sum_{j=1}^q a_{q,j} b_{j,k} \end{bmatrix}$$

Since finite sums always converge, there is no issue exchanging the order of the sums (alternatively set  $j = 1$ , show that  $a_{1,1}$  can be factored and the remaining sum in  $b$  is one, and proceed by cycling through



all  $j$ ), so we have the vector:

$$= \begin{bmatrix} \sum_{j=1}^q \sum_{k=1}^q a_{1,j} b_{j,k} \\ \sum_{j=1}^q \sum_{k=1}^q a_{2,j} b_{j,k} \\ \vdots \\ \sum_{j=1}^q \sum_{k=1}^q a_{q,j} b_{j,k} \end{bmatrix}$$

or

$$= \begin{bmatrix} \sum_{j=1}^q a_{1,j} \sum_{k=1}^q b_{j,k} \\ \sum_{j=1}^q a_{2,j} \sum_{k=1}^q b_{j,k} \\ \vdots \\ \sum_{j=1}^q a_{q,j} \sum_{k=1}^q b_{j,k} \end{bmatrix}$$

For any value of  $j$ ,  $\sum_{k=1}^q b_{j,k} = 1$ , so in effect we have

$$= \begin{bmatrix} \sum_{j=1}^q a_{1,j} \\ \sum_{j=1}^q a_{2,j} \\ \vdots \\ \sum_{j=1}^q a_{q,j} \end{bmatrix}$$

since we know the rows of  $M$  add up to one by hypothesis, we are left with a vector of size  $q \times 1$  with entries all ones, as we wanted to show. Markov matrices are closed under matrix multiplication.

It follows that powers of a Markov matrix are Markov too, since we are multiplying Markov matrices by (the same) Markov matrix.

(2) The rather particular Markov matrix

$$M = \begin{bmatrix} 0 & A \\ B & 0 \end{bmatrix}$$

has second power:

$$M^2 = \begin{bmatrix} AB & 0 \\ 0 & BA \end{bmatrix}$$

A remark: since  $M^2$  is Markov, it follows that the  $n \times n$  submatrix  $AB$  and the  $p \times p$  submatrix  $BA$  are Markov too.

Now rewrite  $B = \frac{1}{n} B^*$  so that  $AB = A \frac{1}{n} B^*$  with  $B^*$  is a  $p \times n$  matrix with entries all ones. Then  $AB^*$  adds the rows of  $A$ , which we know are equal to one, and  $AB^* = C$  is a  $n \times n$  matrix with entries all ones. Thus  $AB = \frac{1}{n} C$ .

Rewrite  $BA = \frac{1}{n} B^* A$ . Now let  $B^* A = D$  is a  $p \times p$  matrix with rows that are identical and sum the columns of  $A$ . As before we have that

$$M^2 = \frac{1}{n} \begin{bmatrix} C & 0 \\ 0 & D \end{bmatrix}$$

and

$$M^4 = \frac{1}{n^2} \begin{bmatrix} C^2 & 0 \\ 0 & D^2 \end{bmatrix}$$

Now,  $C^2 = nC$  because of the property of  $C$  being all ones. We resort to a trick to show that  $D^2 = nD$  as well, by writing out the explicit definition of  $D$ :

$$D = \begin{bmatrix} a_1 & a_2 & \cdots & a_p \\ a_1 & a_2 & \cdots & a_p \\ \vdots & \vdots & \ddots & \vdots \\ a_1 & a_2 & \cdots & a_p \end{bmatrix}$$

and

$$D^2 = \begin{bmatrix} a_1 \sum_{i=1}^p a_i & a_2 \sum_{i=1}^p a_i & \cdots & a_p \sum_{i=1}^p a_i \\ \vdots & \vdots & \ddots & \vdots \\ a_1 \sum_{i=1}^p a_i & a_2 \sum_{i=1}^p a_i & \cdots & a_p \sum_{i=1}^p a_i \end{bmatrix}$$

or

$$D^2 = \left( \sum_{i=1}^p a_i \right) D$$

Careful,  $D$  is NOT Markov, so that the rows do not sum to 1, but  $D$  was generated summing the columns of  $A$ , a finite (non-Markov) matrix but with rows summing to 1, so that the sum operation in front of the  $D$  is asking us to do the double sum on the entries of  $A$  (sum all the entries of  $A$ ).  $A$  is finite, so let's sum all the rows first and then all the columns (the order of the summing can be exchanged). Since all rows sum to 1, and there are  $n$  rows, it follows we are left with  $n$  as a result, and  $D^2 = nD$ .

[\*\* From a patch-point-of-view, the statement that  $D^2 = nD$ , or  $(\frac{1}{n}D)^2 = \frac{1}{n}D \Leftarrow N^2 = N$  with  $N$  is a Markov matrix with identical rows is analogous to the statement that  $a(x) \star a(x) = a(x)$  with  $a(x)$  is a *Pasquali patch*: at the "powering" level, the  $\star$  operator as I defined it exchanges the integral summation and then adds continuously: the result of this is a uniform distribution (the analogue of the  $n$  in front of the  $D$ ).\*\*]

It is clear now that  $M^4 = M^2$ , and, as before, we use induction to show this is the case for all even powers of this particular matrix. So assume  $M^{2k} = M^2$ , and then  $M^{2(k+1)} = M^{2k}M^2 = M^2M^2 = M^2$  and we are done.

- (3) Since now we know that all even powers are the same, it follows that odd powers are the same too (except possibly the first power):

$$M^{2m+1} = M^{2m}M = M^2M = M^3$$

So all odd powers, except possibly  $M$ , look like  $M^3$ :

$$M^2M = \begin{bmatrix} \frac{1}{n}C & 0 \\ 0 & \frac{1}{n}D \end{bmatrix} \cdot \begin{bmatrix} 0 & A \\ B & 0 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{n}CA \\ \frac{1}{n}DB & 0 \end{bmatrix}$$

The product  $CA$  is a  $(n \times n) \times (n \times p) = (n \times p)$  matrix with identical rows that adds the columns of  $A$ , call it  $D^*$ . On the other hand, the product  $DB = D\frac{1}{n}B^*$  is a  $(p \times p) \times (p \times n) = (p \times n)$  matrix that adds the rows of  $D$  which we already calculated must sum to  $n$ , so all its entries are such. Factor the  $n$ , and we get  $DB = \frac{1}{n}nC^* = C^*$ , with  $C^*$  all entries are ones. Finally, notice  $\frac{1}{n}C^* = B$ . We have:

$$M^3 = \begin{bmatrix} 0 & \frac{1}{n}D^* \\ B & 0 \end{bmatrix}$$

Since  $D^*$  was generated adding the columns of  $A$  (and  $A$  has entries that are nonzero at every row), one can think of several exceptions so that  $\frac{1}{n}D^* \neq A$ , and  $M \neq M^3$ . For example, in the special case where  $n = p$ , let  $A$  be the identity matrix; then  $\frac{1}{n}D^*$  contains entries that are all  $\frac{1}{n}$  and  $\frac{1}{n}D^* \neq A \Rightarrow M \neq M^3$ . □

## 11. APPENDIX

11.1. **Claims in BraKet notation.** Having recently disovered BraKet notation, I am rewriting the claims and proofs to make them easier to understand to a wider audience.

**Definition 11.1.** (*Definition 1.1*) (*May 18, 2013*)

$$f(x, y) \star g(x, y) = \langle f|g \rangle_0^1$$

The  $\int_0^1$  has been added to remind ourselves that we are limiting the dot-product like multiplication to the domain  $[0, 1]^2$ .

11.2. **Proofs in Progress.** Are convergent infinite sums of eigenvalues... descriptive of a finite function? Can we invent new, finite-dot-product functions by looking at convergent infinite sums of eigenvalues? Can we check equivalence of formulas by this method? For the claim where even and odd derivatives are constrained, what happens to periodic functions? Do they have the same invariant, sine and cosine? Sine and cosine plus a phase shift?

What is the relationship to the pythagorean theorem (can we prove it using this method)? Diophantine analysis with this method?

No reason why we should let surfaces be finite sums of  $x$  and  $y$  products.

Groups defined on patchixes or patches

All states are achievable

Alternative ways of writing the star operator (similarity to convolution).

The derivative as progressive shape pathix changes using converging  $\mathbb{P}$

How are zeroes transferred  
Using complex numbers

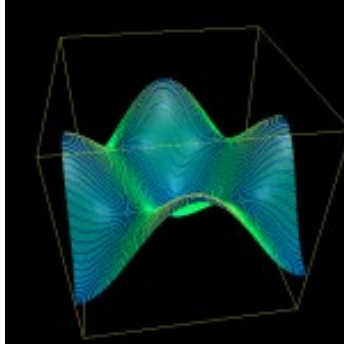


FIGURE 1.  $p(x, y) = 1 - \cos(2\pi x)\cos(2\pi y)$

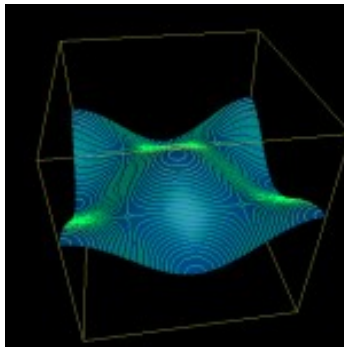


FIGURE 2.  $p_2(x, y) = 1 + \frac{\cos(2\pi x)\cos(2\pi y)}{2}$

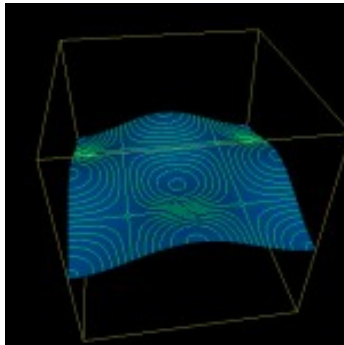


FIGURE 3.  $p_3(x, y) = 1 - \frac{\cos(2\pi x)\cos(2\pi y)}{4}$

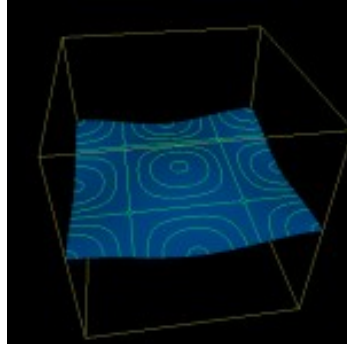


FIGURE 4.  $p_4(x, y) = 1 - \frac{\cos(2\pi x)\cos(2\pi y)}{8}$

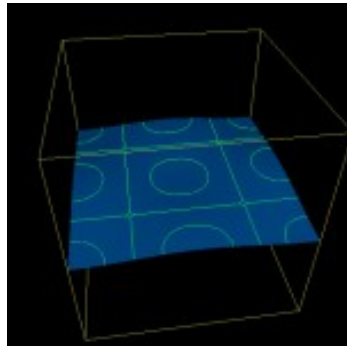


FIGURE 5.  $p_5(x, y) = 1 - \frac{\cos(2\pi x)\cos(2\pi y)}{16}$

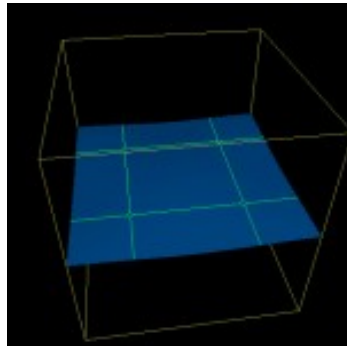


FIGURE 6.  $p_6(x, y) = 1 - \frac{\cos(2\pi x)\cos(2\pi y)}{32}$

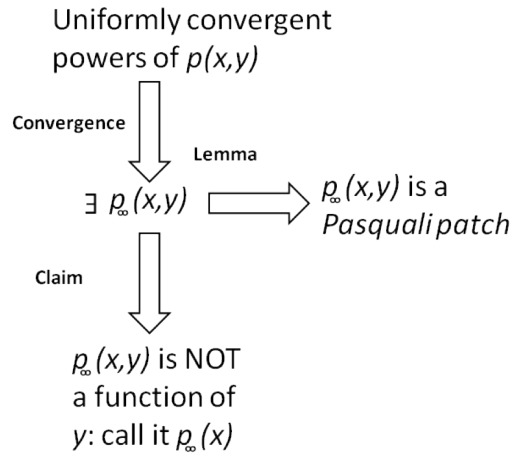


FIGURE 7. Part I

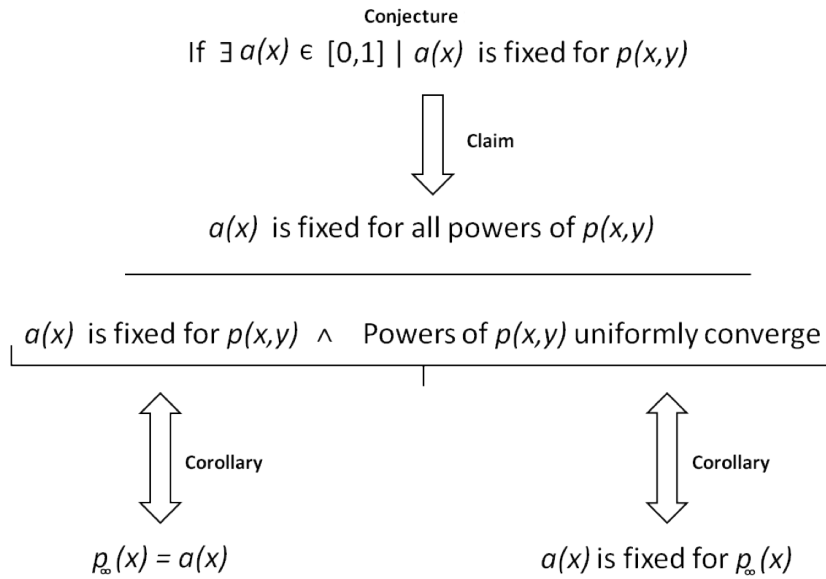


FIGURE 8. Part II

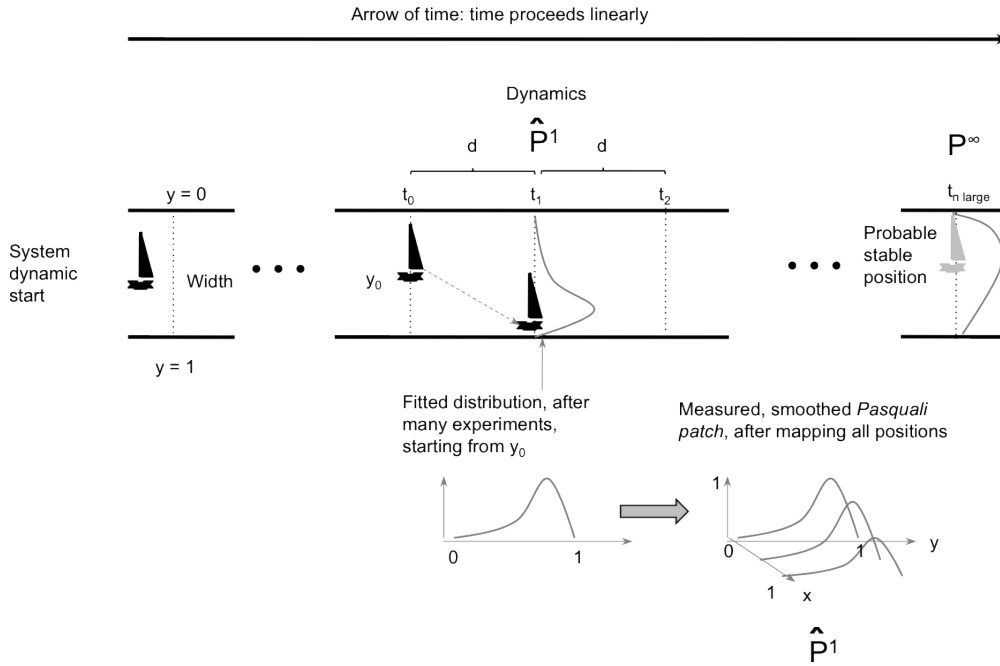


FIGURE 9. We can experimentally create a *Pasquali patch* and use it for prediction. We can perform the measurement at an arbitrary distance.

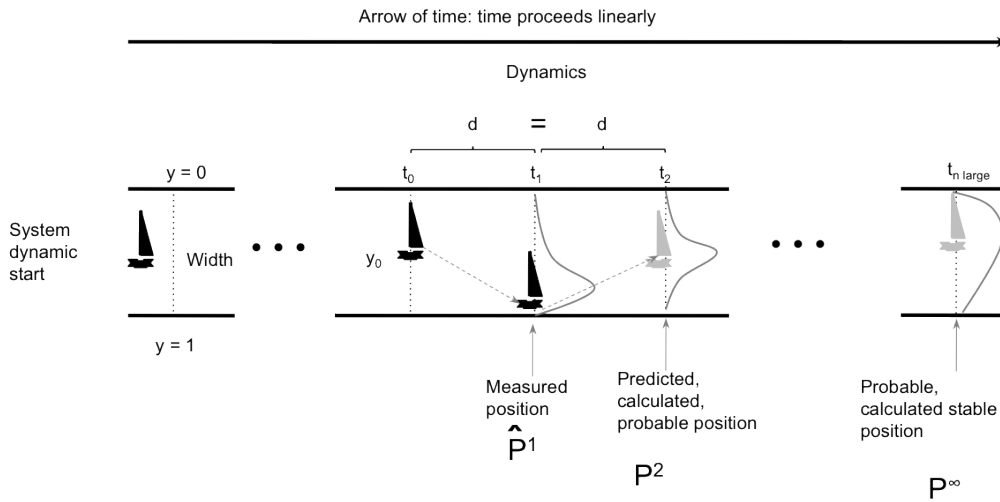


FIGURE 10. We can then use *Pasquali patch* powers for position prediction down the canal, at position  $n \cdot \Delta t$  down the origin.

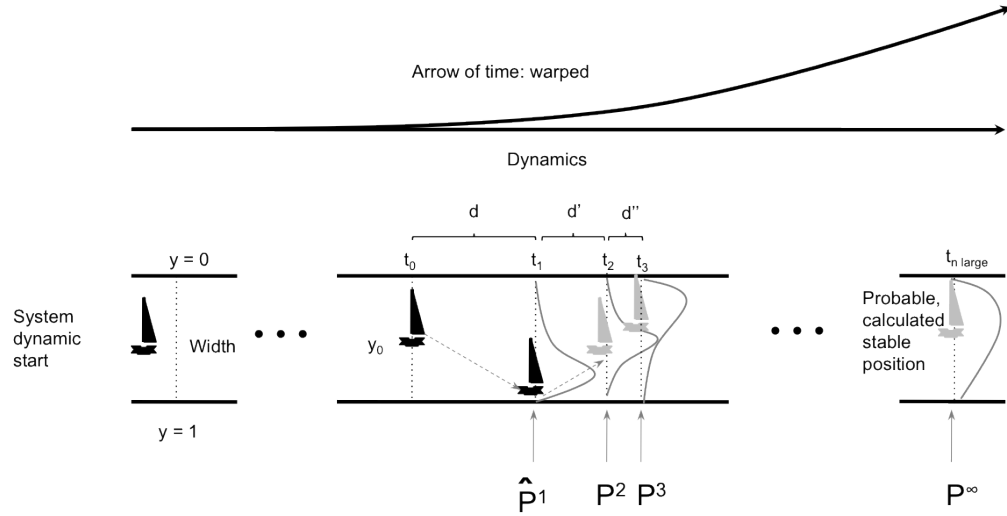


FIGURE 11. In this schematic a *Pasquali patch* and its powers do describe the system, but at non-equidistant points. The arrow of time is warped.

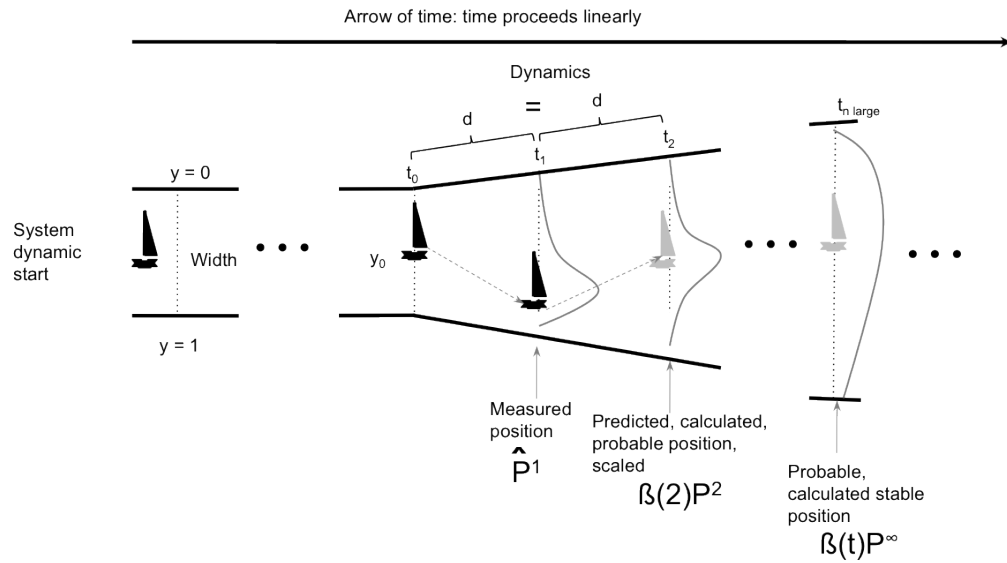


FIGURE 12. In this schematic the width of the canal grows linearly, but *Pasquali patch* dynamics are conserved, suitably scaled.