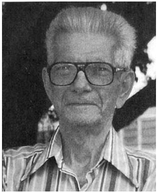 

Fifty Years of Fine and Wilf*

* Well, *almost* fifty years...

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Words

In this talk, I'll be speaking about *words*.

A word is a (possibly) empty string of symbols chosen from a finite nonempty alphabet Σ.

Σ^* is the set of all finite words.

ϵ is the empty word.

$|x|$ denotes the length of the word x, and $|x|_a$ is the number of occurrences of the symbol a in x.

x^k denotes the product $\overbrace{xxx\cdots x}^{k}$.

w^ω is the infinite word $www\cdots$.

If S is a set of words, then S^ω is the set of all infinite words constructed by concatenating elements of S.

Periodicity: The Lyndon-Schützenberger Theorem (1962)

Theorem

Let x, y be nonempty words. Then the following three conditions are equivalent:

(1) $xy = yx$*;*

(2) There exist a nonempty word z and integers $k, \ell > 0$ such that $x = z^k$ and $y = z^\ell$;

(3) There exist integers $i, j > 0$ such that $x^i = y^j$.

However, note that in the implication (1) $\implies$ (2), an even weaker hypothesis suffices: we only need that xy agrees with yx on the first $|x| + |y| - \gcd(|x|, |y|)$ symbols.

Periodicity

We say an infinite sequence $(f_n)_{n\geq 0}$ is *periodic with period length* $h \geq 1$ if $f_n = f_{n+h}$ for all $n \geq 0$. The following is a classical "folk theorem":

Theorem. If $(f_n)_{n\geq 0}$ is an infinite sequence that is periodic with period lengths h and k, then it is periodic with period length $\gcd(h,k)$.

Proof. By the extended Euclidean algorithm, there exist integers $r, s \geq 0$ such that $rh - sk = \gcd(h,k)$. Then we have

$$f_n = f_{n+rh} = f_{n+rh-sk} = f_{n+\gcd(h,k)}$$

for all $n \geq 0$. ■

The Fine-Wilf Paper

- N. J. Fine and H. S. Wilf, "Uniqueness theorems for periodic functions"
- *Proc. Amer. Math. Soc.* **16** (1965), 109–114.
- Submitted August 7 1963, published 1965.
- The Fine-Wilf theorem: a version of the periodicity theorem for finite sequences.
- Answers the question: how long must the finite sequence $(f_n)_{0 \le n < D}$ be for period lengths h and k to imply a period of length $\gcd(h, k)$?
- $D = \operatorname{lcm}(h, k)$ works (of course!), but Fine and Wilf proved we can take $D = h + k - \gcd(h, k)$.

Citation history

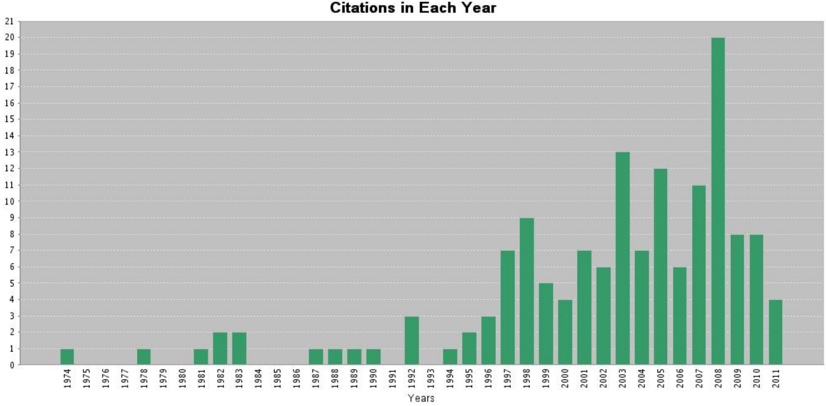

Figure: Citations of Fine-Wilf, according to Web of Science

The Fine-Wilf Theorems

Theorem 1. Let $(f_n)_{n\geq 0}$ and $(g_n)_{n\geq 0}$ be two periodic sequences of period h and k, respectively. If $f_n = g_n$ for $h + k - \gcd(h, k)$ consecutive integers n, then $f_n = g_n$ for all n. The result would be false if $h + k - \gcd(h, k)$ were replaced by any smaller number.

Theorem 2. Let $f(x), g(x)$ be continuous periodic functions of periods α and β, respectively, where $\alpha/\beta = p/q$, $\gcd(p, q) = 1$. If $f(x) = g(x)$ on an interval of length $\alpha + \beta - \beta/q$, then $f = g$. The result would be false if $\alpha + \beta - \beta/q$ were replaced by any smaller number.

Theorem 3. Let $f(x), g(x)$ be continuous periodic functions of periods α and β, respectively, where α/β is irrational. If $f(x) = g(x)$ on an interval of length $\alpha + \beta$, then $f = g$. The result would be false if $\alpha + \beta$ were replaced by any smaller number.

Theorem

Let w and x be nonempty words. Let $\mathbf{y} \in w\{w,x\}^\omega$ and $\mathbf{z} \in x\{w,x\}^\omega$. Then the following conditions are equivalent:

(a) $\mathbf{y}$ *and* $\mathbf{z}$ *agree on a prefix of length at least* $|w| + |x| - \gcd(|w|,|x|)$;

(b) $wx = xw$;

(c) $\mathbf{y} = \mathbf{z}$.

Proof.

(c) $\implies$ (a): Trivial.

(b) $\implies$ (c): By Lyndon-Schützenberger.

We'll prove (a) $\implies$ (b).

Proof.
(a) $\mathbf{y} \in w\{w,x\}^\omega$ and $\mathbf{z} \in x\{w,x\}^\omega$ agree on a prefix of length at least $|w| + |x| - \gcd(|w|,|x|) \Longrightarrow$ (b) $wx = xw$:

We prove the contrapositive. Suppose $wx \neq xw$.

Then we prove that $\mathbf{y}$ and $\mathbf{z}$ differ at a position $\leq |w| + |x| - \gcd(|w|,|x|)$.

The proof is by induction on $|w| + |x|$.

Case 1: $|w| = |x|$ (which includes the base case $|w| + |x| = 2$). Then $\mathbf{y}$ and $\mathbf{z}$ must disagree at the $|w|$'th position or earlier, for otherwise $w = x$ and $wx = xw$; since
$|w| \leq |w| + |x| - \gcd(|w|,|x|) = |w|$, the result follows.

Case 2: $|w| < |x|$.

If w is not a prefix of x, then **y** and **z** disagree on the $|w|$'th position or earlier, and again $|w| \leq |w| + |x| - \gcd(|w|, |x|)$.

So w is a proper prefix of x.

Write $x = wt$ for some nonempty word t.

Now any common divisor of $|w|$ and $|x|$ must also divide $|x| - |w| = |t|$, and similarly any common divisor of both $|w|$ and $|t|$ must also divide $|w| + |t| = |x|$. So $\gcd(|w|, |x|) = \gcd(|w|, |t|)$.

Fine-Wilf: The Proof

Now $wt \neq tw$, for otherwise we have $wx = wwt = wtw = xw$, a contradiction.

Then $\mathbf{y} = ww \cdots$ and $\mathbf{z} = wt \cdots$. By induction (since $|wt| < |wx|$), $w^{-1}\mathbf{y}$ and $w^{-1}\mathbf{z}$ disagree at position $|w| + |t| - \gcd(|w|, |t|)$ or earlier.

Hence $\mathbf{y}$ and $\mathbf{z}$ disagree at position $2|w| + |t| - \gcd(|w|, |t|) = |w| + |x| - \gcd(|w|, |x|)$ or earlier. $\blacksquare$

The proof also implies a way to get words that optimally "almost commute", in the sense that xw and wx should agree on as long a segment as possible.

Theorem

For each $m, n \geq 1$ there exist binary words x, w of length m, n, respectively, such that xw and wx agree on a prefix of length $m + n - \gcd(m, n) - 1$ but differ at position $m + n - \gcd(m, n)$.

These words are the finite *Sturmian words*.

Indeed, our proof even provides an algorithm for computing these words:

$$S(h, k) = \begin{cases} (0^h, 0^{h-1}1), & \text{if } h = k \ ; \\ (x, w), & \text{if } h > k \text{ and } S(k, h) = (w, x) \ ; \\ (w, wt), & \text{if } h < k \text{ and } S(h, k - h) = (w, t) \ . \end{cases}$$

Since 1965

Since 1965, research on Fine-Wilf has been in three areas:

- applications (esp. to string-searching algorithms such as Knuth-Morris-Pratt)
- generalizations (esp. to more than 2 numbers; partial words)
- variations (e.g., to abelian periods; to inequalities)

Fine-Wilf and String Searching

The famous linear-time string searching algorithm of Knuth-Morris-Pratt finds all occurrences of a pattern p in a text t in time bounded by $O(|p| + |t|)$.

It compares the pattern to a portion of the text beginning at position i, and, when a mismatch is found, shifts the pattern to the right based on the position of the mismatch.

The worst-case in their algorithm comes from "almost-periodic" words, where long sequences of matching characters occur without a complete match.

It turns out that such words are precisely the maximal "counterexamples" in the Fine-Wilf theorem (the Sturmian pairs).

Multiple Periods

Many authors have worked on generalizations to multiple periods: Castelli, Justin, Mignosi, Restivo, Holub, Simpson & Tijdeman, Constantinescu & Ilie, Tijdeman & Zamboni, ...

For example, Castelli, Mignosi, and Restivo (1999) proved that for three periods $p_1 \leq p_2 \leq p_3$ the appropriate bound is

$$\frac{1}{2}(p_1 + p_2 + p_3 - 2\gcd(p_1, p_2, p_3) + h(p_1, p_2, p_3))$$

where h is a function related to the Euclidean algorithm on three inputs.

Partial words

Partial words: words together with “don't care” symbols called “holes”. Holes match each other and all other symbols.

Theorem

There exists a computable function $L(h, p, q)$ such that if a word w with h holes with periods p and q is of length $\geq L(h, p, q)$, then w also has period $\gcd(p, q)$.

Berstel and Boasson (1999) proved we can take $L(1, p, q) = p + q$.

Shur and Konovalova (2004) proved we can take $L(2, p, q) = 2p + q - \gcd(p, q)$.

Many results by Blanchet-Sadri and co-authors.

Variations on Fine & Wilf

Fine & Wilf works for equalities. How about inequalities?

For example, suppose $\mathbf{f} = (f_n)_{n \geq 0}$, $\mathbf{g} = (g_n)_{n \geq 0}$ are two periodic sequences of period h and k, respectively. Suppose $f_n \leq g_n$ for a prefix of length D. We want to conclude that $f_n \leq g_n$ everywhere.

Here the correct bound is $D = \mathrm{lcm}(h, k)$. Example: take

$$\begin{aligned} \mathbf{f} &= (1^{h-1}2)^\omega \\ \mathbf{g} &= (2^{k-1}1)^\omega \end{aligned}$$

Then $f_n \leq g_n$ for $0 \leq n < \mathrm{lcm}(h, k) - 1$, but the inequality fails at $n = \mathrm{lcm}(h, k) - 1$.

So we need some additional hypothesis.

Theorem. Let $\mathbf{f} = (f_n)_{n\geq 0}$, $\mathbf{g} = (g_n)_{n\geq 0}$ be two periodic sequences of real numbers, of period lengths h and k, respectively, such that

$$\sum_{0\leq i<h} f_i \geq 0 \tag{1}$$

and

$$\sum_{0\leq j<k} g_j \leq 0. \tag{2}$$

Let $d = \gcd(h, k)$.

(a) If

$$f_n \leq g_n \quad \text{for } 0 \leq n < h + k - d \tag{3}$$

then $f_n = g_n$ for all $n \geq 0$.

(b) The conclusion (a) would be false if in the hypothesis $h + k - d$ were replaced by any smaller integer.

Sketch of Proof, Part (a)

Define

$$\begin{aligned} P(z) &= 1 + z + \cdots + z^{h-1} = (z^h - 1)/(z-1); \\ Q(z) &= 1 + z + \cdots + z^{k-1} = (z^k - 1)/(z-1); \\ R(z) &= (z^k - 1)/(z^d - 1); \quad d = \gcd(h,k) \\ S(z) &= (z^h - 1)/(z^d - 1). \end{aligned}$$

By hypothesis $P \circ \mathbf{f} \geq 0$, where by $\circ$ we mean take the dot product of the coefficients of P with consecutive overlapping windows of $\mathbf{f}$. Then $R \circ (P \circ \mathbf{f}) \geq 0$. But then $RP \circ \mathbf{f} \geq 0$.

Sketch of Proof, Part (a)

Similarly, the hypothesis

$$\sum_{0 \le j < k} g_j \le 0$$

means $Q \circ (-\mathbf{g}) \ge 0$.
Then $SQ \circ (-\mathbf{g}) \ge 0$.
But $RP = SQ$, so

$$\sum_{0 \le i < h+k-d} e_i(f_i - g_i) \ge 0. \tag{4}$$

where $R(z)P(z) = \sum_{0 \le i < h+k-d} e_i z^i$.

It can be shown that the e_i are strictly positive, so since $f_n \le g_n$ for $0 \le n < h+k-d$, we get $f_n = g_n$ for $0 \le n < h+k-d$.

By the Fine & Wilf theorem, $f_n = g_n$ for $n \ge 0$. ■

Maximal Counter-Examples

Maximal counter-examples in (b) can be deduced as the *first differences* of the maximal counter-examples to Fine & Wilf (the Sturmian pairs).

For example, for $h = 5$, $k = 8$ we have $w = (-1, 1, -1, 0, 1)$ and $x = (0, 1, -1, 0, 1, -1, 1, -1)$. Then

n	0	1	2	3	4	5	6	7	8	9	10	11	12
f_n	-1	1	-1	0	1	-1	1	-1	0	1	-1	1	-1
g_n	0	1	-1	0	1	-1	1	-1	0	1	-1	0	1

Another variation

Suppose we have two periodic sequences of integers, say $(f_n)_{n\geq 0}$ of period h and $(g_n)_{n\geq 0}$ of period k. For how many consecutive terms can $f_n + g_n$ strictly decrease?

The answer, once again, is

$$h + k - \gcd(h, k).$$

Here is an example achieving $h + k - 1$ for $h = 5, k = 8$:

n	0	1	2	3	4	5	6	7	8	9	10	11	12
$f(n)$	0	−16	8	−8	−24	0	−16	8	−8	−24	0	−16	8
$g(n)$	0	15	−10	5	20	−5	10	−15	0	15	−10	5	20
$f+g$	0	−1	−2	−3	−4	−5	−6	−7	−8	−9	−10	−11	28

Morphisms

A *morphism* is a map h from Σ^* to Δ^* such that

$$h(xy) = h(x)h(y)$$

for all words x, y.

It follows that h can be uniquely specified by providing its image on each letter of Σ.

For example, let

$$\begin{aligned} h(0) &= \texttt{r} \\ h(1) &= \texttt{em} \\ h(2) &= \texttt{b} \\ h(3) &= \texttt{er} \end{aligned}$$

Then

$$h(011233) = \texttt{rememberer}.$$

Iterated morphisms

If $\Sigma = \Delta$ we can iterate h. We write

$$\begin{array}{ccc} h^2(x) & \text{for} & h(h(x)), \\ h^3(x) & \text{for} & h(h(h(x))), \\ & \text{etc.} & \end{array}$$

Iterated Morphisms

Iterated morphisms appear in many different areas (often under the name L-systems), including

- models of plant growth in mathematical biology
- computer graphics
- infinite words avoiding certain patterns

An Example from Biology

For example, consider the map φ defined by

$$\begin{aligned} \varphi(a_r) &= a_l b_r \qquad \varphi(a_l) = b_l a_r \\ \varphi(b_r) &= a_r \qquad \varphi(b_l) = a_l \end{aligned}$$

Iterating φ on a_r gives

$$\begin{aligned} \varphi^0(a_r) &= a_r \\ \varphi^1(a_r) &= a_l b_r \\ \varphi^2(a_r) &= b_l a_r a_r \\ \varphi^3(a_r) &= a_l a_l b_r a_l b_r \\ &\vdots \end{aligned}$$

Here the a's represent fat cells and the b's represent thin cells.

This models the development of the blue-green bacterium *Anabaena catenula*.

Iterated Morphisms and Computer Graphics

Szilard and Quinton [1979] observed that many interesting pictures, including approximations to fractals, could be coded using iterated morphisms.

A beautiful book by Prusinkiewicz and Lindenmayer provides many examples.

Iterated Morphisms and Computer Graphics

Example: code a picture using "turtle graphics" where R codes a move followed by a right turn, L codes a move followed by a left turn, and S codes a move straight ahead with no turn.

Consider the map g defined as follows:

$$\begin{aligned} g(R) &= RLLSRRLR \\ g(L) &= RLLSRRLL \\ g(S) &= RLLSRRLS \end{aligned}$$

By iterating g on $RRRR$ we get

$$\begin{aligned} g^0(R) &= RRRR \\ g^1(R) &= RLLSRRLRRLLSRRLRRLLS\cdots \end{aligned}$$

These words code successive approximations to a von Koch fractal curve.

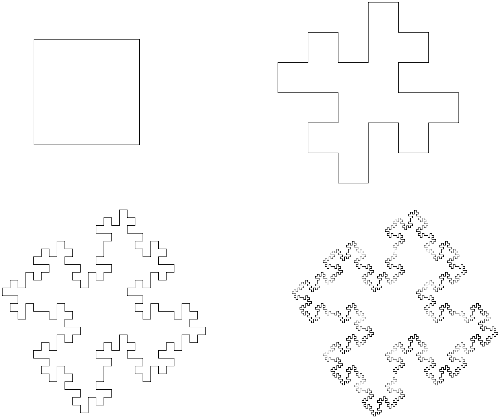

Figure: Four iterations in the construction of the von Koch curve

The Matrix Associated with a Morphism

Given a morphism $\varphi : \Sigma^* \to \Sigma^*$ for some finite set $\Sigma = \{a_1, a_2, \ldots, a_d\}$, we define the *incidence matrix* $M = M(\varphi)$ as follows:

$$M = (m_{i,j})_{1 \le i,j \le d}$$

where $m_{i,j}$ is the number of occurrences of a_i in $\varphi(a_j)$, i.e., $m_{i,j} = |\varphi(a_j)|_{a_i}$.

Example. Consider the morphism φ defined by

$$\varphi : \mathtt{a} \to \mathtt{ab}, \qquad \mathtt{b} \to \mathtt{cc} \qquad \mathtt{c} \to \mathtt{bb}.$$

Then

$$M(\varphi) = \begin{array}{c} \\ \mathtt{a} \\ \mathtt{b} \\ \mathtt{c} \end{array} \begin{array}{c} \begin{array}{ccc} \mathtt{a} & \mathtt{b} & \mathtt{c} \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & 2 \\ 0 & 2 & 0 \end{pmatrix} \end{array}$$

The Matrix Associated with a Morphism

The matrix $M(\varphi)$ is useful because of the following proposition.

Proposition. We have

$$\begin{bmatrix} |\varphi(w)|_{a_1} \\ |\varphi(w)|_{a_2} \\ \vdots \\ |\varphi(w)|_{a_d} \end{bmatrix} = M(\varphi) \begin{bmatrix} |w|_{a_1} \\ |w|_{a_2} \\ \vdots \\ |w|_{a_d} \end{bmatrix}.$$

Proof. We have

$$|\varphi(w)|_{a_i} = \sum_{1 \le j \le d} |\varphi(a_j)|_{a_i} \; |w|_{a_j}.$$

∎

The Matrix Associated with a Morphism

Corollary.

$$\begin{bmatrix} |\varphi^n(w)|_{a_1} \\ |\varphi^n(w)|_{a_2} \\ \vdots \\ |\varphi^n(w)|_{a_d} \end{bmatrix} = (M(\varphi))^n \begin{bmatrix} |w|_{a_1} \\ |w|_{a_2} \\ \vdots \\ |w|_{a_d} \end{bmatrix}$$

Hence we find

Corollary.

$$|\varphi^n(w)| = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \end{bmatrix} M(\varphi)^n \begin{bmatrix} |w|_{a_1} \\ |w|_{a_2} \\ \vdots \\ |w|_{a_d} \end{bmatrix}.$$

The Length Sequence of an Iterated Morphism

We can now ask questions about the sequence of lengths

$$|x|, \ |h(x)|, \ |h^2(x)|, \ \ldots$$

These questions were very popular in mathematical biology (L-systems) in the 1980's.

For example, here is a classical result:

Theorem. Suppose $h : \Sigma^* \to \Sigma^*$ is a morphism, and suppose there exist a word $w \in \Sigma^*$ and a constant c such that

$$c = |w| = |h(w)| = \cdots = |h^n(w)|,$$

where $n = |\Sigma|$. Then $c = |h^i(w)|$ for all $i \geq 0$.

Proof of the Theorem

It suffices to show $|h^{n+1}(w)| = c$, because then the theorem follows by induction on n.

Let M be the incidence matrix of h. By the Cayley-Hamilton theorem,

$$M^n = c_0 M^0 + \cdots + c_{n-1} M^{n-1}$$

for some constants $c_0, c_1, \ldots, c_{n-1}$.

Define $f_i = |h^i(w)|$ and let

$$v = [|w|_{a_1} \ |w|_{a_2} \ \cdots \ |w|_{a_n}]^T.$$

Then for $0 \leq i < n$ we have

$$\begin{aligned} f_{i+1} - f_i &= [1\ 1 \cdots 1](M^{i+1} - M^i)v \\ &= [1\ 1 \cdots 1]M^i(M - I)v \\ &= [1\ 1 \cdots 1]M^i v' = 0, \end{aligned}$$

where $v' := (M - I)v$.

Proof of the Theorem

Now

$$\begin{aligned} f_{n+1} - f_n &= [1\ 1 \cdots 1]M^n v' \\ &= [1\ 1 \cdots 1](c_0 + \cdots + c_{n-1}M^{n-1})v' \\ &= \sum_{0 \le i < n} c_i [1\ 1 \cdots 1] M^i v' \\ &= 0, \end{aligned}$$

since each summand is 0.

Hence $f_{n+1} = f_n$. ■

Another Question

We might also ask, how long can the sequence of lengths

$$|x|, \ |h(x)|, \ |h^2(x)|, \ \ldots$$

strictly decrease?

This question arose naturally in a paper with Wang characterizing the two-sided infinite fixed points of morphisms, i.e., those two-sided infinite words $\mathbf{w}$ such that $h(\mathbf{w}) = \mathbf{w}$.

The Length Sequence of an Iterated Morphism

If Σ has n elements, we can easily find a decreasing sequence of length n. For example, for $n = 5$, define h as follows:

$$\begin{aligned} h(\mathtt{a}) &= \mathtt{b} \\ h(\mathtt{b}) &= \mathtt{c} \\ h(\mathtt{c}) &= \mathtt{d} \\ h(\mathtt{d}) &= \mathtt{e} \\ h(\mathtt{e}) &= \epsilon \end{aligned}$$

Then we have

$$\begin{aligned} h(\mathtt{abcde}) &= \mathtt{bcde} \\ h^2(\mathtt{abcde}) &= \mathtt{cde} \\ h^3(\mathtt{abcde}) &= \mathtt{de} \\ h^4(\mathtt{abcde}) &= \mathtt{e} \\ h^5(\mathtt{abcde}) &= \epsilon \end{aligned}$$

The Length Sequence of an Iterated Morphism

So

$$\begin{aligned} |\texttt{abcde}| &> |h(\texttt{abcde})| > |h^2(\texttt{abcde})| > |h^3(\texttt{abcde})| \\ &> |h^4(\texttt{abcde})| > |h^5(\texttt{abcde})| = 0. \end{aligned}$$

The Decreasing Length Conjecture

Conjecture. If $h : \Sigma^* \to \Sigma^*$, and Σ has n elements, then

$$|w| > |h(w)| > \cdots > |h^k(w)|$$

implies that $k \leq n$.

Another way to state the Decreasing Length Conjecture is the following:

Conjecture. Let M be an $n \times n$ matrix with non-negative integer entries. Let v be a column vector of non-negative integers, and let u be the row vector $[1\ 1\ 1\ \cdots\ 1]$. If

$$uv > uMv > uM^2v > \cdots > uM^kv$$

then $k \leq n$.

Path Algebra

There is a nice correspondence between directed graphs and non-negative matrices, as follows:

If G is a directed graph on n vertices, we can construct a non-negative matrix

$$M(G) = (m_{i,j})_{1 \leq i,j \leq n}$$

as follows: let

$$m_{i,j} = \begin{cases} 1, & \text{if there is a directed edge from} \\ & \text{vertex } i \text{ to vertex } j \text{ in } G; \\ 0, & \text{otherwise.} \end{cases}$$

Then the number of distinct walks of length n from vertex i to vertex j in G is just the i,j'th entry of M^n.

Path Algebra

Similarly, given a non-negative $n \times n$ matrix $M = (m_{i,j})_{1 \le i,j \le n}$ we may form its associated graph $G(M)$ on n vertices, where we put a directed edge from vertex i to vertex j iff $m_{i,j} > 0$.

A Useful Lemma

Lemma. Let $r \geq 1$ be an integer, and suppose there exist r sequences of real numbers $\mathbf{b}_i = (b_i(n))_{n \geq 0}$, $1 \leq i \leq r$, and r positive integers $h_1, h_2, \ldots, h_r$, such that the following conditions hold:

(a) $b_i(n + h_i) \geq b_i(n)$ for $1 \leq i \leq r$ and $n \geq 0$;

(b) There exists an integer $D \geq 1$ such that $\sum_{1 \leq i \leq r} b_i(n) > \sum_{1 \leq i \leq r} b_i(n+1)$ for $0 \leq n < D$.

Then $D \leq h_1 + h_2 + \cdots + h_r - r$.

A Useful Lemma

Remark. When $r = 2$ and $\gcd(h_1, h_2) = 1$, then it can be shown that the bound in this Lemma is tight.

For example, for $h_1 = 5$, $h_2 = 8$ we find

n	0	1	2	3	4	5	6	7	8	9	10	11	12
$b_1(n)$	0	-16	8	-8	-24	0	-16	8	-8	-24	0	-16	8
$b_2(n)$	0	15	-10	5	20	-5	10	-15	0	15	-10	5	20
$b_1(n) + b_2(n)$	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	28

Proof of the Decreasing Length Conjecture

Theorem. Suppose M is an $n \times n$ matrix with non-negative integer entries. If there exist a row vector u and a column vector v with non-negative integer entries such that

$$uv > uMv > uM^2v > \cdots > uM^kv,$$

then $k \leq n$. Also $k = n$ only if $M^n = 0$.

Proof.

- Let M be the matrix in the statement of the theorem and G its associated graph.
- Let $u = (u_1, u_2, \ldots, u_n)$ and $v = (v_1, v_2, \ldots, v_n)^T$.
- Let V be the set of vertices in G.
- Consider some maximal set of vertices forming disjoint cycles $\{C_1, C_2, \ldots, C_r\}$ in G.
- Then V can be written as the disjoint union

  $$V = C_1 \ \cup \ C_2 \ \cup \ \cdots \ \cup \ C_r \ \cup \ W,$$

  where W is the set of vertices which do not lie in any of the disjoint cycles.

- Any directed walk in G of length $|W|$ or greater must intersect some cycle C_i, for otherwise the walk would contain a cycle disjoint from $C_1, C_2, \ldots, C_r$.
- Associate each walk of length $\geq |W|$ with the first cycle C_i it intersects.
- Define $P^s_{i,j,l}$ to be the number of directed walks of length s from vertex i to vertex j associated with cycle l.
- Also define

$$T^s_l := \sum_{1 \leq i,j \leq n} u_i v_j P^s_{ijl}.$$

- Then for any $s \geq |W|$ we have

$$uM^s v = \sum_{1 \leq l \leq r} T^s_l. \tag{5}$$

- Then
$$T_l^s \le T_l^{s+|C_l|},$$
since any walk of length s associated with cycle C_l can be extended to a walk of length $s+|C_l|$ by traversing the cycle C_l once.
- From the inequality $uM^s v > uM^{s+1} v$ for $0 \le s \le k-1$ and Eq. (5) we have
$$\sum_{1\le l\le r} T_l^s > \sum_{1\le l\le r} T_l^{s+1}$$
for $|W| \le s < k$.
- Now for $1 \le i \le r$ and $j \ge 0$ define $b_i(j) = T_i^{|W|+j}$ and $h_i = |C_i|$.
- Then the conditions of the previous Lemma are satisfied.

- We conclude that

$$k - |W| \leq |C_1| + |C_2| + \cdots + |C_r| - r.$$

- Moreover

$$|C_1| + |C_2| + \cdots + |C_r| + |W| = |V| = n$$

  and so $k \leq n - r$.

- Finally $k = n$ implies that $r = 0$, so G is acyclic and $M^n = 0$.

So the Decreasing Length Conjecture is proved.

For Further Reading

1. N. J. Fine and H. S. Wilf, Uniqueness theorems for periodic functions, *Proc. Amer. Math. Soc.* **16** (1965), 109–114.
2. J. Shallit and M.-w. Wang, On two-sided infinite fixed points of morphisms, *Theoret. Comput. Sci.* **270** (2002), 659–675.
3. S. Cautis, F. Mignosi, J. Shallit, M.-w. Wang, S. Yazdani, Periodicity, morphisms, and matrices, *Theoret. Comput. Sci.* **295** (2003), 107–121.