Analysis of Pattern Occurances

Course 1: Complexity Analysis of String Algorithms

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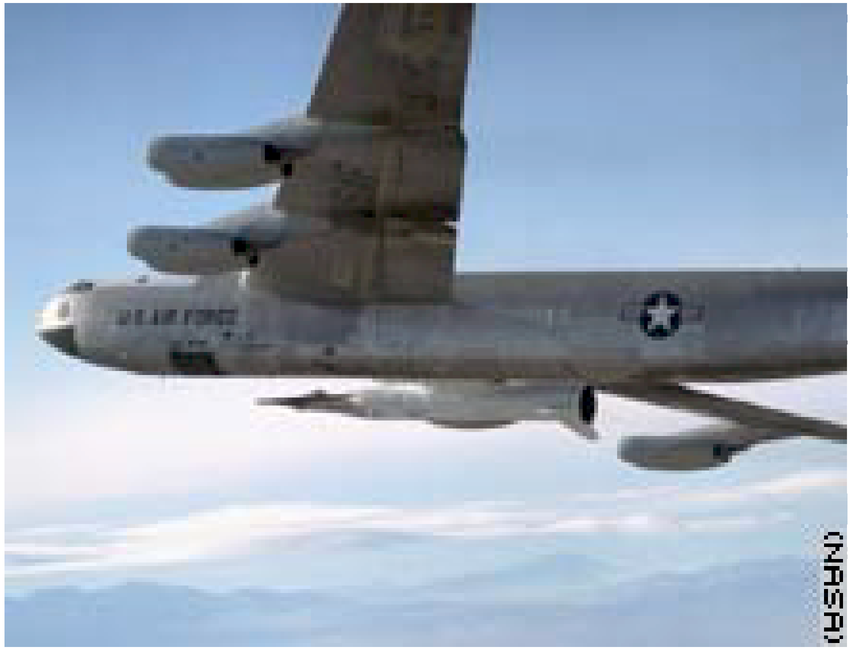
Preliminaries

Math or Mach?

"It's relatively simple in its concept," said Griff Corpening, chief engineer for the X-43A program. "It's incredibly challenging in its execution.... [That is] where all those days of research come in."



Abstract

One counts the number of occurrences of a given pattern H in a text of size n. This number is denoted $O_n(H)$.

Frequency analysis relies on the decomposition of the text T onto languages, the so-called initial, minimal, and tail languages.

Going from there to their generating functions both for a Markovian and a Bernoulli environment, it turns out the whole counting problem only depends on $P(H)$ and the "correlation set".

Markov sequence

A sequence $X_1, X_2, ...$ of random variates is called a *Markov sequence* of order 1 iff, for any n,

$$F(X_n|X_{n-1}, X_{n-2}, ...X_1) = F(X_n|X_{n-1})$$

i.e., if the conditional distribution F of X_n, assuming $X_{n-1}, X_{n-2}, ...X_1$

equals

the conditional distribution F of X_n assuming only X_{n-1}.

Markov chain

If a Markov sequence of random variates X_n take the *discrete values* $a_1, ..., a_N$ then

$$P(x_n = a_{in} | x_{n-1} = a_{in-1}, ..., x_1 = a_{i1}) = P(x_n = a_{in} | x_{n-1} = a_{in-1})$$

and the sequence x_n is called a *Markov chain* of order 1.

Correlation of patterns

A *correlation* of two patterns X (size m) and Y is a string, denoted by XY, over the set $\Omega = \{0, 1\}$.

$$|XY| = |X|$$

Each position i can be computed as

$i = 1 \Leftrightarrow$ place Y at $X_i \wedge$ all overlapping pairs are identical

else $i = 0$

Example of pattern correlation

Let $\Omega = \{M, P\}$, $X = MPMPPM$ and $Y = MPPMP$.
Then XY can be deduced in the following manner:

```
X: HTHTTH
Y: HTTHT           0
     HTTHT         0
       HTTHT       1
         HTTHT     0
           HTTHT   0
             HTTHT 1
```

whilst YX can be shown to equal 00010

Representation of the correlation

Other representations of either string:

1. as a number in some base t. Thus, e.g. $XY_2 = 9$

2. as a polynomial. Thus, e.g. $XY_t = t^3 + 1$

Autocorrelation

Furthermore, *autocorrelation* of X can be defined as XX.

It represents the periods of X, i.e. those shifts of X that cause that pattern to overlap itself.

Using $Y = MPPMP$ from our previous example, YY evaluates to 10010

Using $A = MMM$, AA evaluates to 111

Autocorrelation set

Given a string H, the autocorrelation *set* A_{HH} or just A is defined as

$$A_{HH} = \{H_{k+1}^{m} : H_1^k = H_{m-k+1}^{m}\}$$

Example of an autocorrelation set

Let $H = SOS$
The autocorrelation reveals to be

$$HH = 101$$

whereas the autocorrelation set in that case is

$$A = \{\epsilon, 01\}$$

Let's play a game

The Penny game - invented by Penney.

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This is because of the "optimal" autocorrelation

Sources

Bernoulli

A *Bernoulli Source*, or *memoryless source*, generates text randomly.

Every subsequent symbol (of a finite alphabet) is created independently of its predecessors, and the probability of each symbol is not necesserily the same.

If it is, the Source is called a *symmetric*, or *unbiased* Bernoulli Source.

If text over an alphabet S is generated by a Bernoulli Source, then each symbol $s \in S$ *always* occurs with probability $P(s)$.

Markovian Source (1)

A *Markovian Source* generates symbols based not on the *a priori* probability of each symbol.

Instead, it only heeds a (finite) set of predecessors to ascertain the probability of each next symbol.

In order to do so, it requires a *memory* of previously emitted symbols.

Markovian Source (2)

Text generated by a Markovian Source is a realization of a Markov sequence of order K.

K denotes the number of previous symbols that the probability of the next symbol depends on.

In our application, this sequence will be stationary and $K = 1$, i.e. a first-order Markov sequence.

When computing the next symbol, we only need to observe the last symbol.

Markovian Source (3)

In our case $(K = 1)$, the transition matrix is defined by

$$P = \{p_{i,j}\}_{i,j \in S}$$

where

$$p_{i,j} = \text{Probability } (t_{k+1} = j | t_k = i)$$

The matrix entry (i, j) denotes the conditional probability of the next symbol being j if the current symbol is i.

Generating functions of languages

What is a language, after all

A language L is a collection of words.

This collection must satisfy certain properties to belong to a specific language.

Thus, we can associate with a language L its generating function $L(z)$.

Generating functions

Given a sequence $\{a_n\}_{n\geq 0}$, we know its generating function is defined as

$$A(z) = \sum_{n\geq 0} a_n z^n$$

Generating functions, too

For sinister purposes, we represent it differently as

$$A(z) = \sum_{\alpha \in S} z^{w(\alpha)}$$

where S is a set of objects (words ...) and $w(\alpha)$ is a weight function.

Henceforth we will interpret it as the size of α, i.e. $w(\alpha) = |\alpha|$

The equivalence becomes evident when we set a_n to be the number of objects α satisfying $w(\alpha) = n$.
Now we have a more combinatorial view

Generating function of a language

Now, for any language L, we define its generating function $L(z)$ as

$$L(z) = \sum_{w \in L} P(w) z^{|w|}$$

where $P(w)$ is the probability of word w's occurence and $|w|$ is the length of w.

So the coefficient of $z^{|w|}$ is the sum of the probabilites all words of that length.

In addition, we assume that $P(\epsilon) = 1$. So every language includes the empty word (as we know).

Conditional generating function

In addition, the H-conditional generating function of L is given as

$$
\begin{aligned}
L_H(z) &= \sum_{w \in L} P(w | w_{-m} = h_1 \dots w_{-1} = h_m) z^{|w|} \\
&= \sum_{w \in L} P(w | w_{-m}^{-1} = H) z^{|w|}
\end{aligned}
$$

where w_{-i} is the symbol preceding the first character of w at distance i.

We use this definition for Markovian sources, where the probability depends on the previous symbols.

Example: autocorrelation generating function

In our previous example, the autocorrelation set was

$$A = \{\epsilon, 01\}$$

The generating function of the set is

$$A(z) = 1 + \frac{z^2}{4}$$

given a Bernoulli source, and

$$A_{SOS}(z) = 1 + p_{SO} p_{OS} z^2$$

given a Markovian source of order one.

Formulating our objective

We will now formulate the special generating functions whose closed form we will later strive to compute:

1. $T^{(r)}(z) = \sum_{n\geq 0} Pr(O_n(H) = r)z^n$

2. $T(z,u) = \sum_{r=1}^{\infty} T^{(r)}(z)u^r$

   $= \sum_{r=1}^{\infty} \sum_{n=0}^{\infty} Pr(O_n(H) = r)z^n u^r$

Declaring languages

Introduction

Let H be a given pattern.

- The *initial language* R is the set of words containing only **one** occurrence of H, located at the **right** end.
- The *tail language* U is defined as the set of words u such that Hu has exactly **one** occurrence of H, which occurs at the **left** end.
- The *minimal language* M is the set of words w such that Hw has exactly **two** occurrences of H, located at its **left** and **right** ends.

Component languages

We differentiate several special languages, given a pattern H.
"$\cdot$" stands for concatenation of words.

1. $R = \{r : r \in T_1 \wedge H$ occurs at the right end of $r\}$

2. $U = \{u : H \cdot u \in T_1\}$

3. $M = \{w : H \cdot w \in T_2 \wedge H$ occurs at the right end of $H \cdot w\}$

Language relationships

Qualities of T_r

At first, we will try to describe the languages T and T_r in terms of R, M and U:

$\forall r \geq 1$:

$$T_r = R \cdot M^{r-1} \cdot U$$

Composition proof (T_r)

Proof: First occurance of H in a T_r word determines the prefix

$$p$$

which is in R.

From that prefix on, we look onward until the next occurance of H.

The found word w is $\in M$.

After $r-1$ iterations, we add a H-devoid suffix, which is in U, because its prefix has H at the end.

$\square$

Qualities of T

The "extended" version of T_r, its words including an arbitrary number of H occurrences, can be composed similarily:

$$T = R \cdot M^* \cdot U$$

where $M^* := \bigcup_{r=0}^{\infty} M^r$

Composition proof (T)

Proof:

A word belongs to T, if for some $1 \leq r < \infty$ it belongs to T_r.

As $\bigcup_{r=1}^{\infty} M^{r-1} = \bigcup_{r=0}^{\infty} M^r = M^*$, the assertion is proven.

$\square$

Four more relationships

Analyzing the relationships between M, U and R further, we introduce

1. W, the set of all words
2. S, the alphabet set
3. the operators "+" and "-", which denote disjoint union and language subtraction

Four more relationships I (1)

$$\bigcup_{k \geq 1} M^k = W \cdot H + (A - \{e\})$$

Proof:

$\leftarrow$:

Let k be the number how often H occurs in $W \cdot H$.

$k \geq 1$.

The *last* occurrence of H in every included word is on the right.

That means, that $W \cdot H \subseteq \bigcup_{k \geq 1} M^k$.

Four more relationships I (2)

$\rightarrow$:

Let $w \in \bigcup_{k \geq 1} M^k$.

Iff $|w| \geq |H|$, then surely the inclusion is correct.

Iff $|w| < |H|$ (how can that be?), then $w \notin W \cdot H$.

But then, necessarily, $w \in A - \{\epsilon\}$, because the second H in Hw overlaps with the first H by definition (it is element of M^k), so w must be in the autocorrelation set A.

$\square$

Four more relationships II

$$U \cdot S = M + U - \{e\}$$

Proof:

All words of S consist of a single character s.

Given a word $u \in U$ and concatenating them, we differentiate two cases.

If Hus contains a second occurrence of H, it is clearly at the right end. Then $us \in M$.

If Hus does contain only a single H, then us must be non-empty word of U.

□

Four more relationships III

$$H \cdot M = S \cdot R - (R - H)$$

Proof:

$\rightarrow$:

Let sw be a word in $H \cdot M$, $s \in S$ (we can write every such word in this way WLOG).

sw contains exactly two times H, evidently at its left, and also at its right end.
Thus, sw is also $\in S \cdot R$

$\leftarrow$:

If a word swH from $S \cdot R$ is not in R, then because it contains a second H starting at the left end of sw, because $wH \in R$.
Of course, in that case it is $\in H \cdot M$.

□

Four more relationships IV

$$T_0 \cdot H = R \cdot A$$

Proof:

Let wH be $\in T_0 \cdot H$. Then there can be either be one or more occurences of H in wH, one of which is at the right end.

If there is no second one, then wH is $\in R$ by definition of R

If, however, there is a second one, then it overlaps somehow with the first one.

So we view the word until the end of the *first* H, which is in R. Due to the overlapping, the remaining part is $\in A$.

$\square$

One more

Combining relationships II and III yields

$$H \cdot U \cdot S - H \cdot U = (S - \epsilon)R$$

No proof is necessary, as we have validated both ingredients.

Using II, the left side is $H(U \cdot S - U) = H \cdot M$

The right side is

$$\begin{aligned} S \cdot R - R & \\ &= S \cdot R - (R \cap S \cdot R) \\ &= S \cdot R - (R - H) \end{aligned}$$

Together, that is just relationship III.

Languages & Generating Functions

In the Bernoulli env. (1)

We will now transcend from languages to their generating functions.
Given any language L_1, we know its generating function to be

$$A_1(z) = \sum_{w \in L_1} P(w) z^{|w|}$$

In the Bernoulli env. (2)

So what is the the result of multiplying two languages (i.e. concatenating them) in respect to their gen. func.? What is $L_3 = L_1 \cdot L_2$?

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$$

! The assumption $P(wv) = P(w)P(v)$ only holds true with a

memoryless source.

"Particularities"

A few particular cases:

- S (alphabet set) $\Rightarrow S(z) = \sum_{s \in S} P(s) z^{|s|} = z$

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- $\{\epsilon\} \Rightarrow E(z) = \sum_{w \in \{\epsilon\}} P(w) z^{|w|} = 1 \cdot 1 = 1$
- $H \Rightarrow H(z) = \sum_{w = H} P(H) z^{|H|} = P(H) z^m$

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- $\{\epsilon\} \Rightarrow E(z) = \sum_{w \in \{\epsilon\}} P(w) z^{|w|} = 1 \cdot 1 = 1$
- $H \Rightarrow H(z) = \sum_{w=H} P(H) z^{|H|} = P(H) z^m$
- W (behold, the set of *all* words)
  $\Rightarrow W(z) = \sum P(w) z^{|k|} = \sum_{k \geq 0} z^k = \frac{1}{1-z}$

Looking for Generating Functions

Translating I

We will now attempt to translate our known language relationships into generating functions:
In case I only, the formula we derive is correct just for a memoryless source.

$$\bigcup_{k\geq 1} M^k = W \cdot H + (A - \{e\})$$

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$$\sum_{k=0}^{\infty} M_H(z)^k - 1 = \frac{1}{1-z} \cdot P(H) z^m + A_H(z) - 1$$

$$\frac{1}{1-M_H(z)} = \frac{1}{1-z} \cdot P(H) z^m + A_H(z)$$

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$$U_H(z) = \frac{M_H(z) - 1}{(z-1)}$$

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$$P(H)z^m M_H(z) - P(H)z^m = S(z) \cdot R(z) - R(z)$$

$$P(H)z^m (M_H(z) - 1) = R(z)(z - 1)$$

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$$R(z) = P(H)z^m \frac{M_H(z) - 1}{z - 1}$$

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$$R(z) = P(H) z^m U_H(z)$$

Main findings I

$T^{(r)}(z)$

We remember, that for $r \geq 1$

$$T_r = R \cdot M^{r-1} \cdot U$$

We have now gleaned every component, and can translate it (for $r \geq 1$) into

$$T^{(r)}(z) = R(z) M^{r-1}(z) U_H(z)$$

We do also remember, that

$$T = R \cdot M^* \cdot U$$

As T is the language with *any* number of Hs, its generating function is indeed ...

$$T(z, u) = R(z) \frac{u}{1 - uM_H(z)} U_H(z)$$

Preliminaries
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GF of languages
Declaring languages
Language relationships
Languages & GFs
Looking for GFs
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- What is left to do?
- Using derivatives
- Proof Preparations
- Closed form formula (1)
- Closed form formula (2)
- Main findings II
Epilogue

On to other shores

What is left to do?

We still have no formula of gathering $O_n(H)$, i.e. the frequency of H-occurrences ($|H| = m$) in random text of length n over an alphabet S with $|S| = V$.

Let us make an educated guess, though.
What we do not know, is how important *overlapping* is.
Assuming to disregard that topic, the answer *could* be

$$E[O_n(H)] = P(H)(n - m + 1)$$

It is.

But why?

Using derivatives

Looking at our bivariate generating function of T,

$$T(z,u) = \sum_{r=1}^{\infty} \sum_{n=0}^{\infty} Pr(O_n(H) = r) z^n u^r$$

we notice that we would like the two sums to be reversed.

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$$T_u(z,u) = \sum_{r=1}^{\infty} \sum_{n=0}^{\infty} Pr(O_n(H) = r) z^n r \text{ (=\#Occ) } u^{r-1}$$

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... and setting u to 1 leads to ...

$$T_u(z,1) = \sum_{n=0}^{\infty}(\sum_{r=1}^{\infty} Pr(O_n(H) r) z^n$$

Proof Preparations

To shorten things, we introduce

$$D_H(z) = (1 - z)A_H(z) + z^m P(H)$$

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and

$$R(z) = z^m P(H) \frac{1}{D_H(z)}$$

Deriving the closed form formula (1)

$$T_u(z, u)$$

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$$T_u(z,u)$$

$$= R(z)U_H(z)\frac{u}{(1-uM_H)}\frac{d}{du}$$

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$$
\begin{aligned}
T_u(z, u) & \\
&= R(z) U_H(z) \frac{u}{(1 - uM_H)} \frac{d}{du} \\
&= R(z) U_H(z) \frac{(1 - uM) + uM}{(1 - uM_H)^2}
\end{aligned}
$$

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&\quad = R(z)U_H(z)\frac{1}{(1-uM_H)^2}
\end{aligned}
$$

Deriving the closed form formula (2)

u is now set to 1 due to the previous calculus:

$$T_u(z, 1)$$

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&T_u(z,1)\\
&\qquad = R(z)U_H(z)\frac{1}{(1-M_H)^2}\\
&\qquad = R(z)U_H(z)(1-1+\frac{z-1}{D_H(z)})^{-2}
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&= R(z)\frac{1}{D_H(z)}\frac{D_H(z)^2}{(z-1)^2} \\
&= z^m P(H)\frac{1}{D_H(z)}\frac{D_H(z)}{(z-1)^2}
\end{aligned}
$$

Deriving the closed form formula (2)

Preliminaries
Sources
GF of languages
Declaring languages
Language relationships
Languages & GFs
Looking for GFs
Main findings I
On to other shores
- What is left to do?
- Using derivatives
- Proof Preparations
- Closed form formula (1)
- Closed form formula (2)
- Main findings II

Epilogue

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T_u(z,1) & \\
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&= R(z)U_H(z)\frac{D_H(z)^2}{(z-1)^2} \\
&= R(z)\frac{1}{D_H(z)}\frac{D_H(z)^2}{(z-1)^2} \\
&= z^m P(H)\frac{1}{D_H(z)}\frac{D_H(z)}{(z-1)^2} \\
&= \frac{z^m P(H)}{(z-1)^2}
\end{aligned}
$$

Main findings II

As the text has length n, we are extracting the nth coefficient of $T_u(z, 1)$, and *voilà*

$$E[O_n] = [z^n]T_u(z, 1)$$

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\begin{aligned}
E[O_n] &= [z^n]T_u(z,1) \\
&= P(H)[z^n]z^m(1-z)^{-2}
\end{aligned}
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Main findings II

As the text has length n, we are extracting the nth coefficient of $T_u(z,1)$, and *voilà*

$$\begin{aligned} E[O_n] &= [z^n]T_u(z,1) \\ &= P(H)[z^n]z^m(1-z)^{-2} \\ &= P(H)[z^{n-m}](1-z)^{-2} \end{aligned}$$

Main findings II

As the text has length n, we are extracting the nth coefficient of $T_u(z, 1)$, and *voilà*

$$\begin{aligned} E[O_n] &= [z^n]T_u(z, 1) \\ &= P(H)[z^n]z^m(1-z)^{-2} \\ &= P(H)[z^{n-m}](1-z)^{-2} \\ &= (n-m+1)P(H) \end{aligned}$$

Epilogue

Questions?

"O, call not me to justify the wrong
That thy unkindness lays upon my heart;
Wound me not with thine eye but with thy tongue;
Use power with power and slay me not by art.
What need'st thou wound with cunning when thy might
Is more than my o'er-press'd defense can bide?
That they elsewhere might dart their injuries:
Yet do not so; but since I am near slain,
Kill me outright with looks and rid my pain."
Shakespeare Sonnet CXXXIX

With what certainty (1)

the variance of $E(O_n(H)$ is, for a $r > 1$:

$$Var[O_n(H)] = nc_1 + c_2 + O(r^{-n})$$

where

$$c_1 = P(H)(2A_H(1) - 1 - (2m-1)P(H) + 2P(H)E_1))$$

$$c_2 = P(H)((m-1)(3m-1)P(H) - (m-1)$$
$$(2A_H(1) - 1) - 2A'_H(1)) - 2(2m-1)$$
$$(P(H)^2 E_1 + 2E_2 P(H)^2$$

With what certainty (2)

where E_1, E_2 are

$$E_1 = \frac{1}{\pi_{h1}}[(P - \Pi)Z]_{h_m,h_1}$$

$$E_2 = \frac{1}{\pi_{h1}}[(P^2 - \Pi)Z^2]_{h_m,h_1}$$

Simplification

Luckily (...), for a *memoryless source*, both constants E are void, as P is then equal to Π.
So in that, we have

$$c_1 = P(H)(2A(1) - 1 - (2m-1)P(H))$$

$$c_2 = P(H)((m-1)(3m-1)P(H) - (m-1)(2A(1)-1) - 2A'(1))$$