String Algorithms and Data Structures
Z-values and the Z-algorithm

CS 199-225
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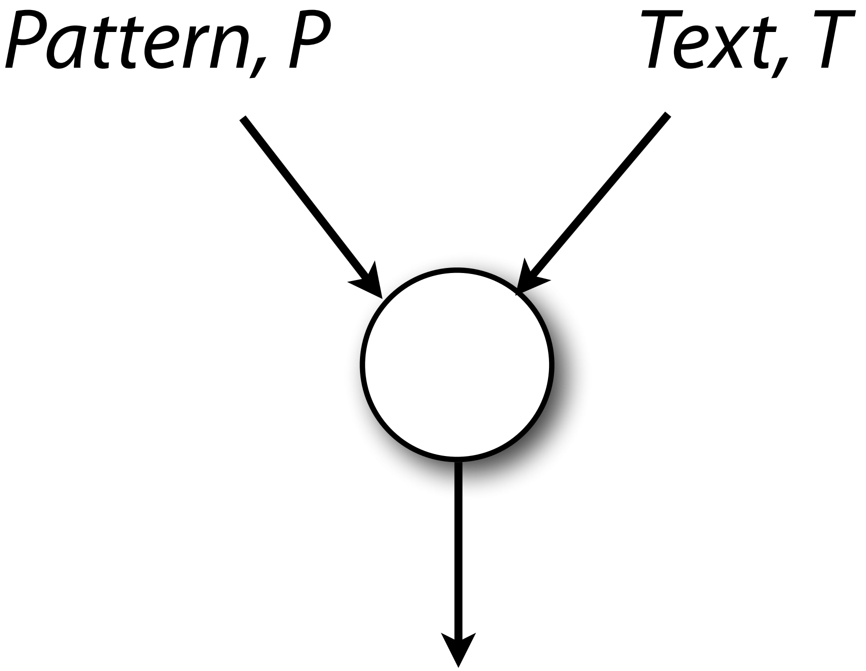
Exact Pattern Matching



Find instances of *P* in *T*

'instances': An exact, full length copy

Exact Pattern Matching

What’s a simple algorithm for exact matching?

```
P: word
T: There would have been a time for such a word
   word word word word word word word word word
    word word word word word word word word
     word word word word word word word word
      word word word word word word word word
       word word word word word word word word
```

One occurrence (the last alignment in the first row, pointing to "word" at the end of T)

Try all possible alignments. For each, check if it matches. This is the *naïve algorithm*.

Exact Pattern Matching

What is good about the naive solution?

What is bad?

Exact Pattern Matching

What is our time complexity? $(n = |P|, \quad m = |T|)$

(# of alignments) x (cost of an alignment)

Exact Pattern Matching

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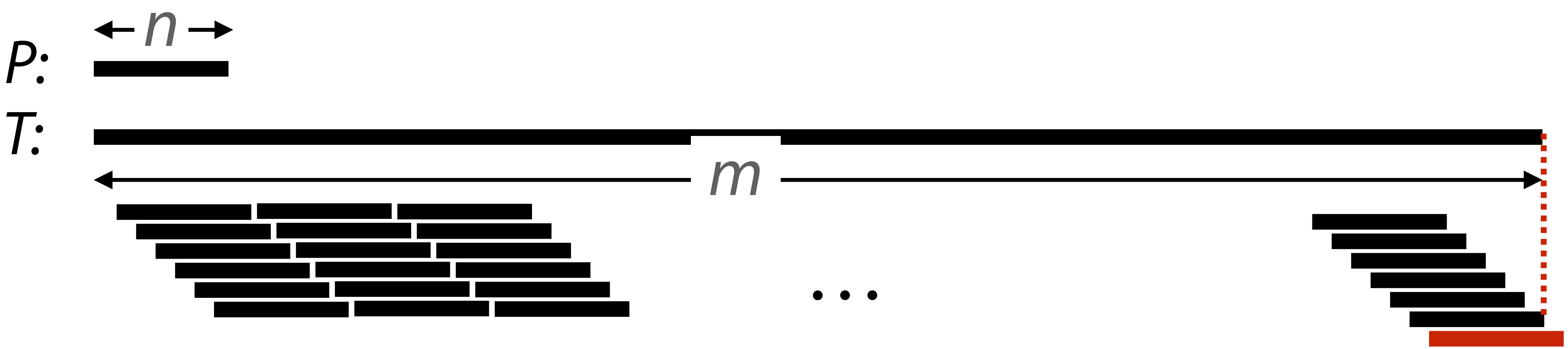


P can fit at each `position' along T except the edge

Exact Pattern Matching

What is our time complexity? $(n = |P|, \quad m = |T|)$

(______________) x (cost of an alignment)

P: **aaaa**

T: **aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa**

aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa
 aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa **aaaa**
  aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa **aaaa**
   aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa **aaaa**
    aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa

There are _______ positions which extend past the edge of T

Exact Pattern Matching

What is our time complexity? $(n = |P|, \quad m = |T|)$

(m-n+1) x (cost of an alignment)

P: **aaaa**

T: **aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa**

aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa
aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa
aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa
aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa
aaaa aaaa aaaa aaaa aaaa aaaa aaaa aaaa

Each alignment compares __________ characters.

Exact Pattern Matching

What is our time complexity? $(n = |P|, \quad m = |T|)$

$$\theta\big((m - n + 1) \times n\big)$$

String Algorithms in Genomics

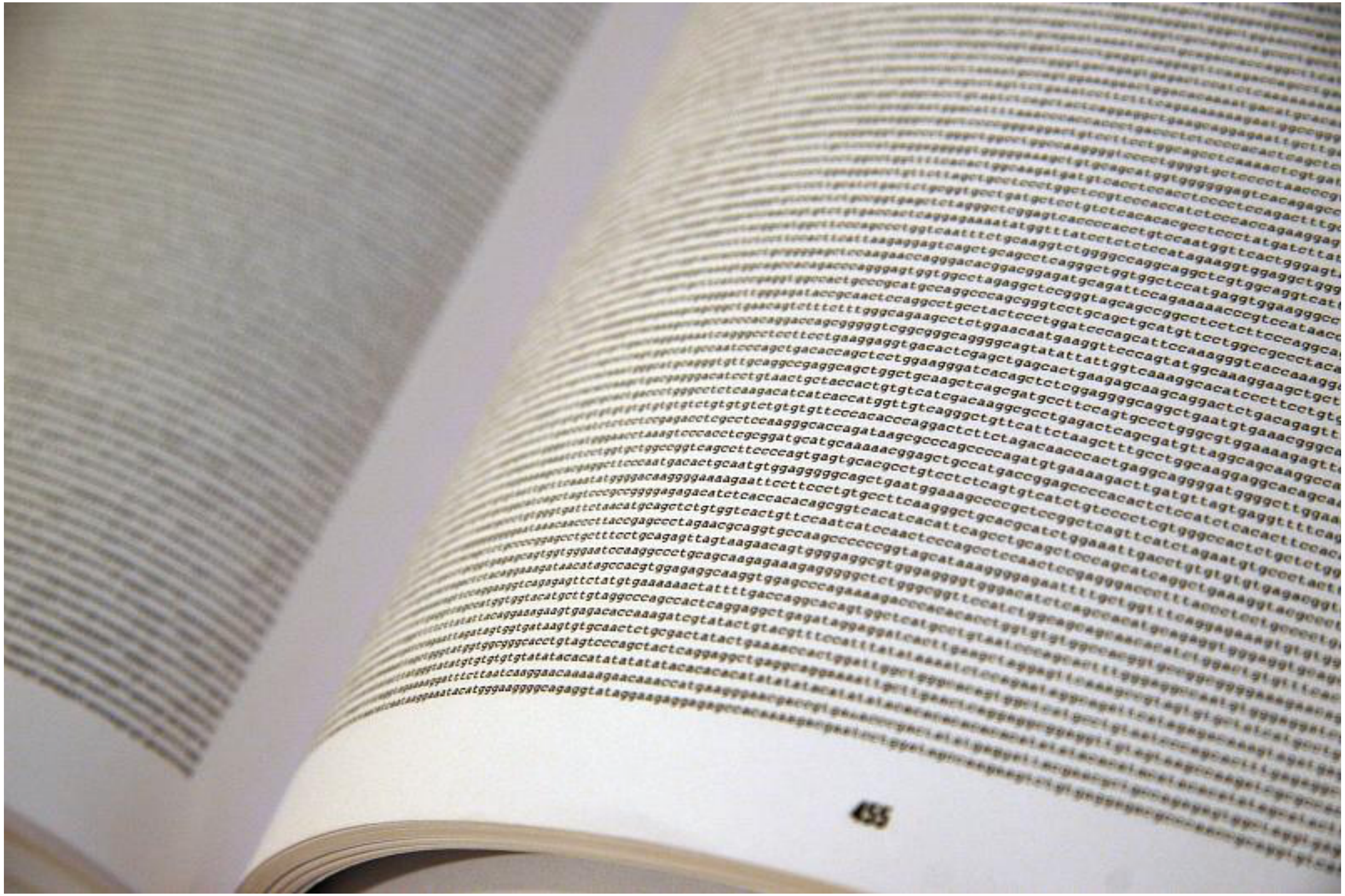
P: Read (n = ~50-150)

CTCAAACTCCTGACCTTTGGTGATCCACCCGCCTAGGCCTTC

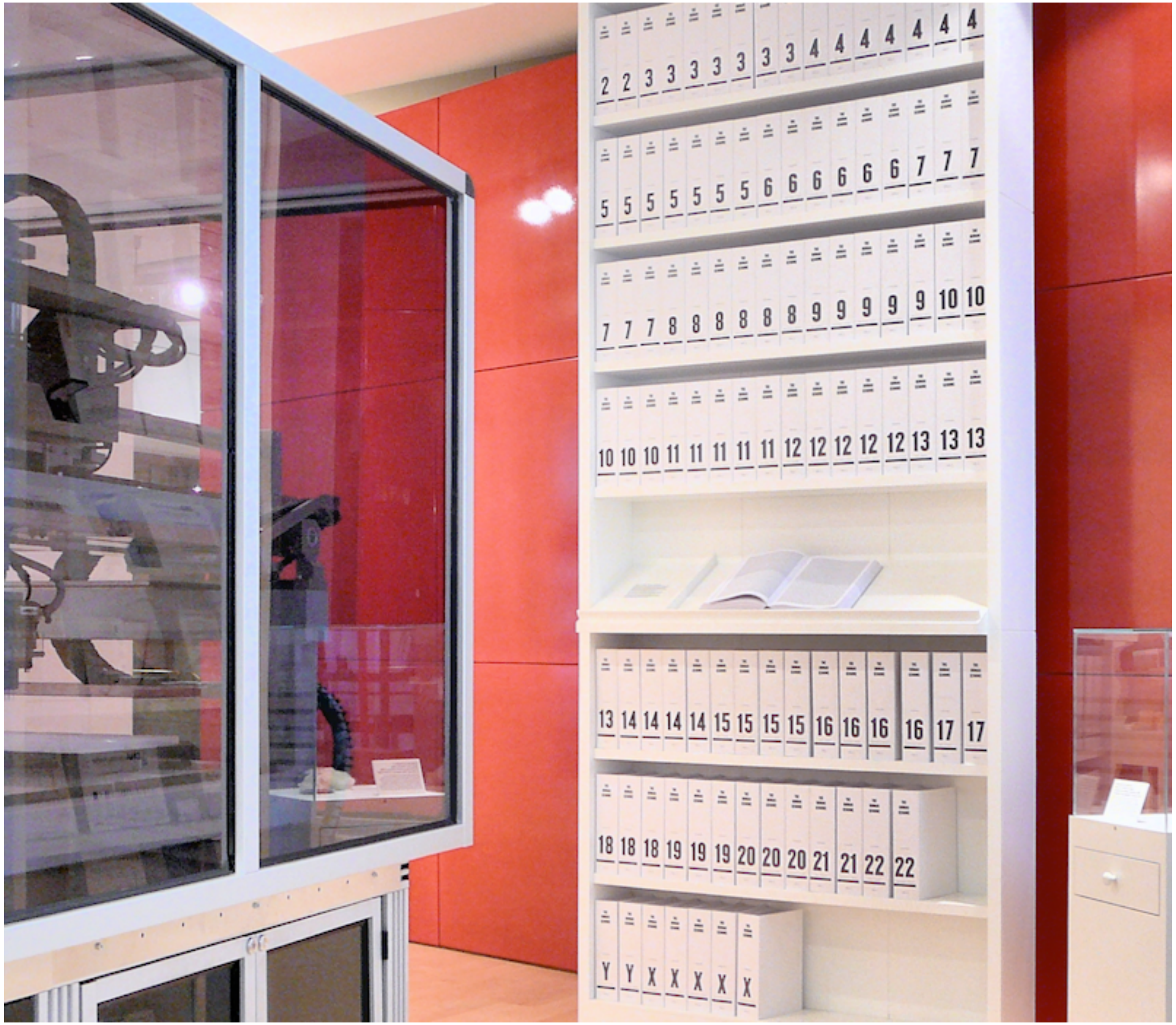
T: Reference (m = ~3 billion)

GATCACAGGTCTATCACCCTATTAACCACTCACGGGAGCTCTCCATGCATTTGGTATTTT
CGTCTGGGGGGTATGCACGCGATAGCATTGCGAGACGCTGGAGCCGGAGCACCCTATGTC
GCAGTATCTGTCTTTGATTCCTGCCTCATCCTATTATTTATCGCACCTACGTTCAATATT
ACAGGCGAACATACTTACTAAAGTGTGTTAATTAATTAATGCTTGTAGGACATAATAATA
ACAATTGAATGTCTGCACAGCCACTTTCCACACAGACATCATAACAAAAAATTTCCACCA
AACCCCCCCTCCCCCGCTTCTGGCCACAGCACTTAAACACATCTCTGCCAAACCCCAAAA
ACAAAGAACCCTAACACCAGCCTAACCAGATTTCAAATTTTATCTTTTGGCGGTATGCAC
TTTTAACAGTCACCCCCCAACTAACACATTATTTTCCCCTCCCACTCCCATACTACTAAT
CTCATCAATACAACCCCCGCCCATCCTACCCAGCACACACACACCGCTGCTAACCCCATA
CCCCGAACCAACCAAACCCCAAAGACACCCCCCACAGTTTATGTAGCTTACCTCCTCAAA
GCAATACACTGACCCGCTCAAACTCCTGGATTTTGGATCCACCCAGCGCCTTGGCCTAAA
CTAGCCTTTCTATTAGCTCTTAGTAAGATTACACATGCAAGCATCCCCGTTCCAGTGAGT
TCACCCTCTAAATCACCACGATCAAAAGGAACAAGCATCAAGCACGCAGCAATGCAGCTC
AAAACGCTTAGCCTAGCCACACCCCCACGGGAAACAGCAGTGATTAACCTTTAGCAATAA
ACGAAAGTTTAACTAAGCTATACTAACCCCAGGGTTGGTCAATTTCGTGCCAGCCACCGC
GGTCACACGATTAACCCAAGTCAATAGAAGCCGGCGTAAAGAGTGTTTTAGATCACCCCC
TCCCCAATAAAGCTAAAACTCACCTGAGTTGTAAAAAACTCCAGTTGACACAAAATAGAC
TACGAAAGTGGCTTTAACATATCTGAACACACAATAGCTAAGACCCAAACTGGGATTAGA
TACCCCACTATGCTTAGCCCTAAACCTCAACAGTTAAATCAACAAAACTGCTCGCCAGAA
CACTACGAGCCACAGCTTAAAACTCAAAGGACCTGGCGGTGCTTCATATCCCTCTAGAGG
AGCCTGTTCTGTAATCGATAAACCCCGATCAACCTCACCACCTCTTGCTCAGCCTATATA
CCGCCATCTTCAGCAAACCCTGATGAAGGCTACAAAGTAAGCGCAAGTACCCACGTAAAG
ACGTTAGGTCAAGGTGTAGCCCATGAGGTGGCAAGAAATGGGCTACATTTTCTACCCCAG
AAAACTACGATAGCCCTTATGAAACTTAAGGGTCGAAGGTGGATTTAGCAGTAAACTAAG
AGTAGAGTGCTTAGTTGAACAGGGCCCTGAAGCGCGTACACACCGCCCGTCACCCTCCTC
AAGTATACTTCAAAGGACATTTAACTAAAACCCCTACGCATTTATATAGAGGAGACAAGT
CGTAACCTCAAACTCCTGCCTTTGGTGATCCACCCGCCTTGGCCTACCTGCATAATGAAG

String Algorithms in Genomics



String Algorithms in Genomics



Improving exact pattern matching

How can we do better than the naïve algorithm?

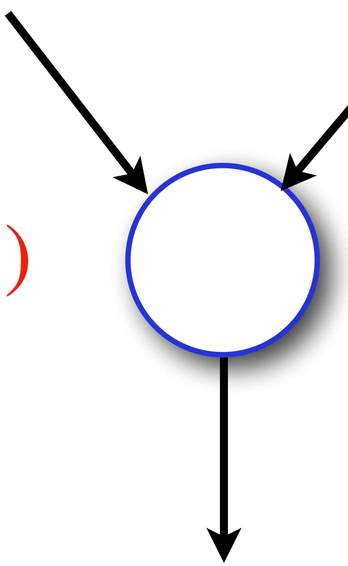
… If we have infinite space?

… If I tell you the pattern ahead of time?

… If I tell you the text ahead of time?

Exact Pattern Matching w/ Z-algorithm

Pattern, P *Text, T*



Naive $\approx \theta(|P||T|)$

Z-Algorithm $\approx \theta(|P| + |T|)$

Find instances of *P* in *T*

'instances': An exact, full length copy

The Z-value [$Z_i(S)$]

Given a string S, $Z_i(S)$ is the length of the longest substring in S, starting at position i, that matches a prefix of S.

	0	1	2	3	4	5	6	7	8	9
S:	**T**	**T**	**C**	**G**	**T**	**T**	**A**	**G**	**C**	**G**

$Z_0(S) =$

$Z_1(S) =$

$Z_2(S) =$

$Z_3(S) =$

$Z_4(S) =$

$Z_5(S) =$

The Z-value [$Z_i(S)$]

Given a string *S*, $Z_i(S)$ is the length of the longest substring in *S*, starting at position *i* , that matches a prefix of *S*.

	0	1	2	3	4	5	6	7	8	9
S:	**T**	**T**	**C**	**G**	**T**	**T**	**A**	**G**	**C**	**G**

$Z_0(S) = 10$

$Z_1(S) = 1$

$Z_2(S) = 0$

$Z_3(S) =$

$Z_4(S) =$

$Z_5(S) =$

The Z-value [$Z_i(S)$]

Given a string S, $Z_i(S)$ is the length of the longest substring in S, starting at position $i > 0$, that matches a prefix of S.

	0	1	2	3	4	5	6	7	8	9
S:	**T**	**T**	**C**	**G**	**T**	**T**	**A**	**G**	**C**	**G**

$Z_0(S) = 10$

$Z_1(S) = 1$

$Z_2(S) = 0$

$Z_3(S) = 0$

$Z_4(S) = 2$

$Z_5(S) = 1$

Calculating the Z-values

Naive: Compute the Z-values by *explicitly* comparing characters (left-to-right scan):

$Z_1 =$

A A A A B A A C A A B A A ...

A A A A B A A C A A B A A ...

$Z_5 =$

A A A A B A A C A A B A A ...

A A A A B A A C A A B A A ...

What is our time complexity?

Calculating the Z-values

Naive: Compute the Z-values by *explicitly* comparing characters (left-to-right scan):

***S*: 1 1 0 1 1 0 0 1**

What is our time complexity?

Calculating the Z-values

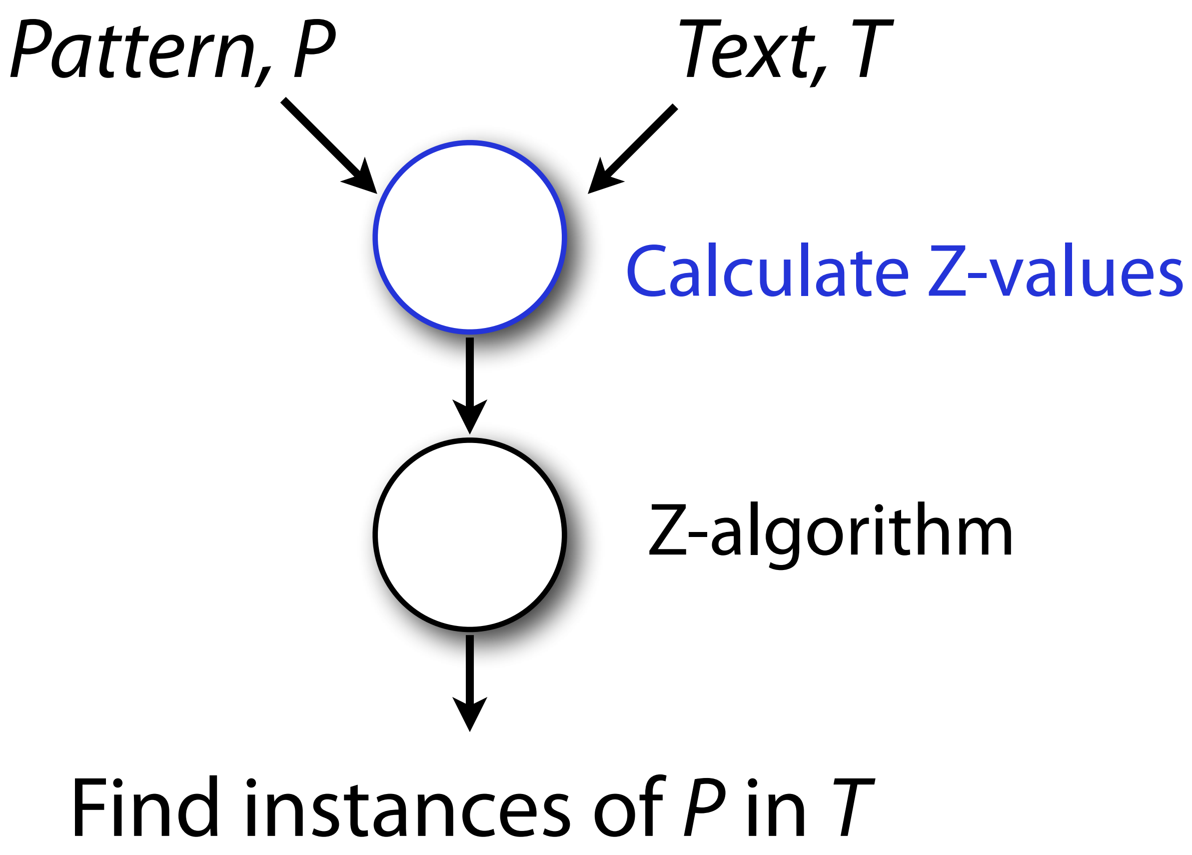
Naive: Compute the Z-values by *explicitly* comparing characters (left-to-right scan):

```
S: 1 1 0 1 1 0 0 1
   1 0 1 1 0 0 1
   0 1 1 0 0 1
   1 1 0 0 1
   1 0 0 1
   0 0 1
   0 1
   1
```

What is our time complexity?

Pattern matching with the Z-value

Given a Z_i value calculator, how do we solve pattern matching?



Z-value Pattern Matching

To solve pattern matching (given *P* and *T*), let ***S* = *P$T***

$ = 'terminal character', outside alphabet

P: **A A** *T*: **A A A A**

S = *P$T*

S: **A A $ A A A A**

Z-value Pattern Matching

To solve pattern matching (given P and T), let $\boldsymbol{S = P\$T}$

$ = 'terminal character', outside alphabet

P: **A A** *T*: **A A A A**

S = P$T

S: **A A $ A A A A**

Z-values

Z(S) = [-, _____, _____, _____, _____, _____, _____]

Z-value Pattern Matching

To solve pattern matching (given *P* and *T*), let ***S* = *P*$*T***

$ = 'terminal character', outside alphabet

P: **A A** *T*: **A A A A**

```
    0 1 2 3 4 5 6
S:  A A $ A A A A
          0 1 2 3
```

$Z(S) = [-, 1, 0, 2, 2, 2, 1]$

What Z_i values are matches?

What are the matching indices in *T*?

Z-value Pattern Matching

P: **T T** *T:* **C T T A**

S:

Z(S):

Z-value search pseudo-code

1. *Concatenate (S=P$T)*

2. *Calculate Z-values for S*

3. For $i<0$, match if $Z_i =$ __________

   Match is ***not*** at i, but instead at

   ____

Assignment 2: a_zval

Learning Objective:

Construct a Z-value calculator and measure its efficiency

Demonstrate use of Z-values in pattern matching

Consider: Our goal is $\theta(|P| + |T|)$. Does Z-value search match this?

End-of-class brainstorm

What information does a single Z-value tell us?

If I know $Z_{i-1}(S)$, can I use that information to help me compute $Z_i(S)$?

The Z-value (Take 2)

Given a string *S*, $Z_i(S)$ is the length of the longest substring in *S*, starting at position *i* , that matches a prefix of *S*.

What information does this give us?

S:

$Z_4(S) = 2$

0	1	2	3	4	5	6	7	8	9	…

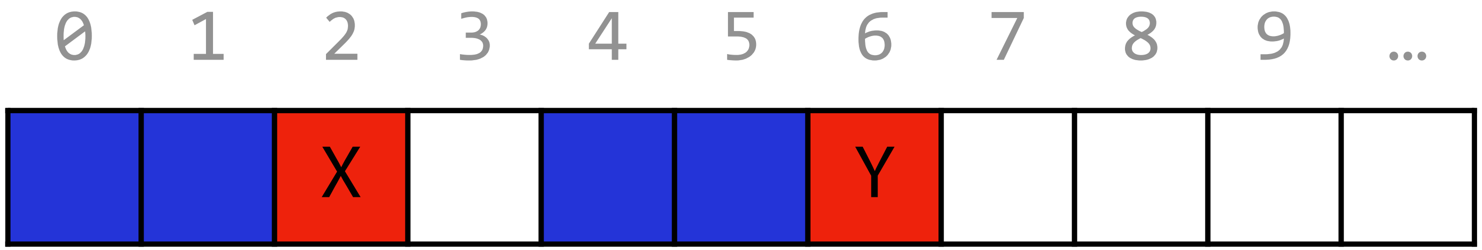
The Z-value (Take 2)

Given a string *S*, $Z_i(S)$ is the length of the longest substring in *S*, starting at position *i* , that matches a prefix of *S*.

What information does this give us?

S:

$$Z_4 = 2$$



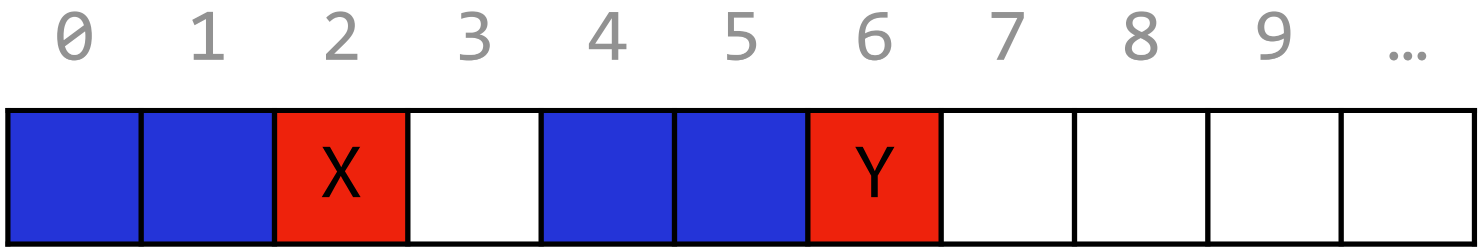
The Z-value (Take 2)

Given a string *S*, $Z_i(S)$ is the length of the longest substring in *S*, starting at position *i* , that matches a prefix of *S*.

What information does this give us?

```
   0 1 2 3 4 5 6 7 8 9
S: T T C G T T A G C G
```

$$Z_4 = 2$$



The Z-Algorithm

Assume we've computed $Z_0, \ldots, Z_{i-1}$ and need to calculate Z_i

Case 1: We know nothing about the characters at S[i]

$Z_1 = ?$

0	1	2	3	4	5	6	7
A	A	A	A	B	B	B	B
A	A	A	A	B	B	B	B

Case 2: We know something about the characters at S[i]

$Z_2 = ?$

0	1	2	3	4	5	6	7
A	A	A	A	B	B	B	B
A	A	A	A	B	B	B	B

The Z-Algorithm

$Z_1 = 3$

$Z_2 = ?$

0	1	2	3	4	5	6	7
A	A	A	A	B	B	B	B
A	A	A	A	B	B	B	B

We track our current knowledge of *S* using three values: i, r, l

i, the current index position being calculated

r, the index of the rightmost character which has ever been matched

l, the index of Z-value which r belongs too

The Z-Algorithm

Start

End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	___	___	___	___	___	___	___
0	**1**	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

	Start	End
i, the current index =		
r, the furthest match char =		
l, the furthest reaching Z-value =		

-	1	__	__	__	__	__	__
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Start End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	1	0	0	__	__	__	__
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Start

End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	1	0	0	__	__	__	__
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Start

End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	1	0	0	3	__	__	__
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Start | End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	1	0	0	3	1	0	__
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Start End

i, the current index =

r, the furthest match char =

l, the furthest reaching Z-value =

-	1	0	0	3	1	0	1
0	1	2	3	4	5	6	7
A	A	B	B	A	A	B	A
A	A	B	B	A	A	B	A

The Z-Algorithm

Intuition: We can use the previous $Z_1, \ldots, Z_i$ to compute Z_{i+1}!

Track 'what we know' using three integers: i, r, l

Next week: Review how integers are updated to define specific cases.