CS 240 – Data Structures and Data Management

Module 9e: String Matching - Enriched

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Based on lecture notes by many previous cs240 instructors

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Winter 2022

version 2022−03−17 08:15

Outline

1. Pattern Matching - details
   - KMP failure function – fast computation
   - KMP failure function – improvement
   - Good suffix array

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KMP failure function – fast computation

$F[j]$ is the length of the longest prefix of P that is a suffix of $P[1..j]$.

- How can we compute this faster?
- Recall property of KMP-automaton of P:
  - If we are in state ℓ, then we have just seen $P[0..\ell-1]$

  $\Leftrightarrow$ $P[0..\ell-1]$ is a suffix of what we have just parsed.

  - Also, KMP is always in the rightmost state where this holds.

  $\Leftrightarrow$ $P[0..\ell-1]$ is the *longest* suffix of what we have just parsed.

  $\Leftrightarrow$ ℓ is the length of the longest prefix of P that is a suffix of what we have just parsed.

KMP failure function – fast computation

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  $\Leftrightarrow$ ℓ is the length of the longest prefix of P
  that is a suffix of what we have just parsed.

Combine this with the definition of $F[j]$ to get:

$F[j] = \ell \Leftrightarrow$
we reach state ℓ when parsing $P[1..j]$ on the KMP-automaton for P

KMP failure function – fast computation

$F[j] =$ **the state we reach when parsing** $P[1..j]$

This immediately gives algorithm: For $j = 1, 2, \ldots,$

- parse $P[1..j]$ on the KMP-automaton for P
- Set $F[j] = \ell$ if we reach state ℓ

KMP failure function – fast computation

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This immediately gives algorithm: For $j = 1, 2, \ldots,$

- parse $P[1..j]$ on the KMP-automaton for P
- Set $F[j] = \ell$ if we reach state ℓ

Observe: We don't need to re-start the parsing from scratch!

- Assume we have computed $F[j]$ already.
- To compute $F[j{+}1]$, parse $P[j{+}1]$ and note reached state.
- So can compute $F[0..m{-}1]$ with *one* parse of $P[1..m{-}1]$

KMP failure function – fast computation

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- Set $F[j] = \ell$ if we reach state ℓ

Observe: We don't need to re-start the parsing from scratch!

- Assume we have computed $F[j]$ already.
- To compute $F[j+1]$, parse $P[j+1]$ and note reached state.
- So can compute $F[0..m-1]$ with *one* parse of $P[1..m-1]$

But isn't this circular?

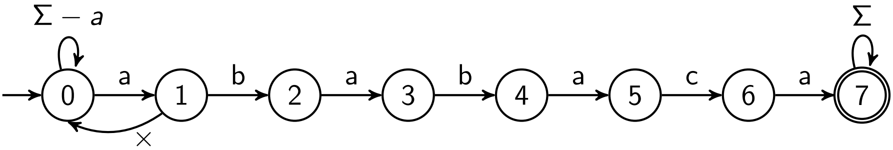
- We need failure-arcs for parsing, but we compute them only now!
- But: To compute $F[j]$, parse $P[1..j-1]$ first ($j-1$ characters)
  $\Rightarrow$ reach state $\leq j$
  $\Rightarrow$ don't need $F[j]$ (= arc from state $j+1$) to parse $P[j]$

Computing the Failure Array

```
KMP::failureArray(P)
P: String of length m (pattern)
    F[0] ← 0
    j ← 1            // index within parsed text
    ℓ ← 0            // reached state
    while j < m do
        if P[j] = P[ℓ]
            ℓ ← ℓ + 1
            F[j] ← ℓ
            j ← j + 1
        else if ℓ > 0
            ℓ ← F[ℓ − 1]
        else
            F[j] ← 0
            j ← j + 1
```

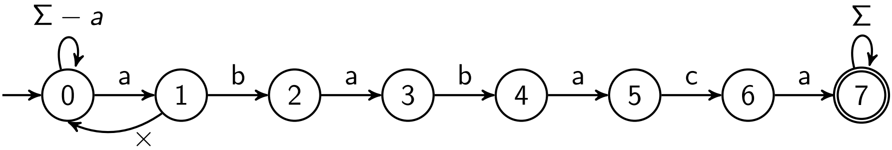
Correctness-idea: $F[j]$ is defined via pattern matching of P in $P[1..j]$. So KMP uses itself! Already-built parts of $F[\cdot]$ are used to expand it.

KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

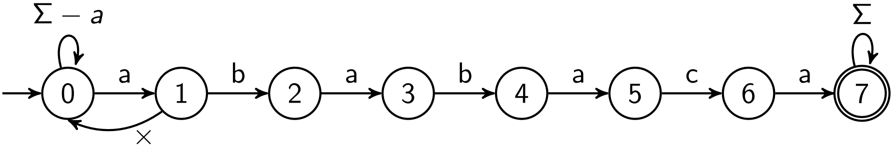
KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

j	1																
$P[i]$																	
$P[j]$																	
ℓ	0																
$F[j]$																	

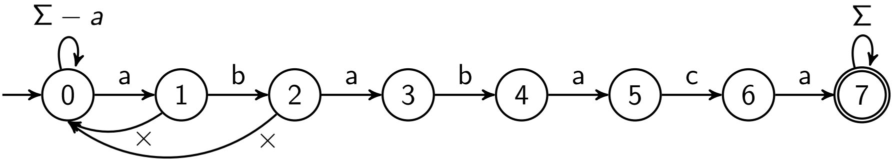
KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

j	1	1														
$P[i]$		b														
$P[j]$		a														
ℓ	0	$\xrightarrow{b}$														
$F[j]$																

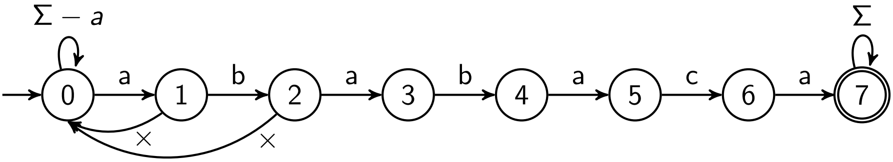
KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

j	1	1	1														
$P[i]$		b															
$P[j]$		a															
ℓ	0	$\xrightarrow{b}$	0														
$F[j]$			0														

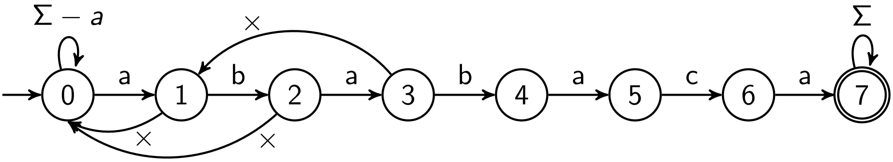
KMP failure function – fast computation



Parse $P[1..m{-}1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2													
$P[i]$		b		a													
$P[j]$		a		a													
ℓ	0	$\stackrel{b}{\to}$	0														
$F[j]$			0														

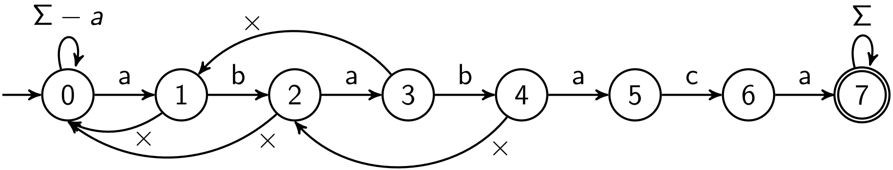
KMP failure function – fast computation



Parse $P[1..m{-}1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2												
$P[i]$		b		a													
$P[j]$		a		a													
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1												
$F[j]$			0		1												

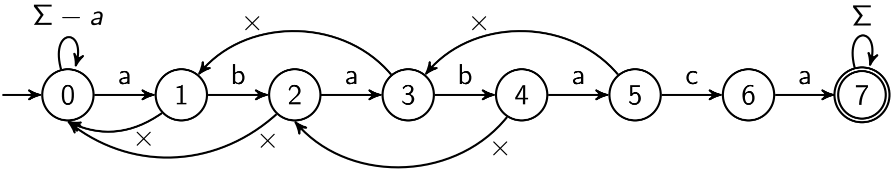
KMP failure function – fast computation



Parse $P[1..m-1] =$ `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3									
$P[i]$		b		a		b										
$P[j]$		a		a		b										
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2									
$F[j]$			0		1		2									

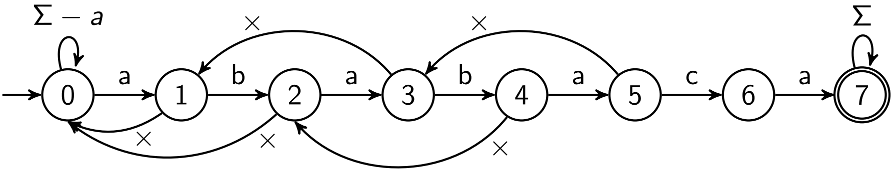
KMP failure function – fast computation



Parse $P[1..m{-}1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4								
$P[i]$		b		a		b		a									
$P[j]$		a		a		b		a									
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3								
$F[j]$			0		1		2		3								

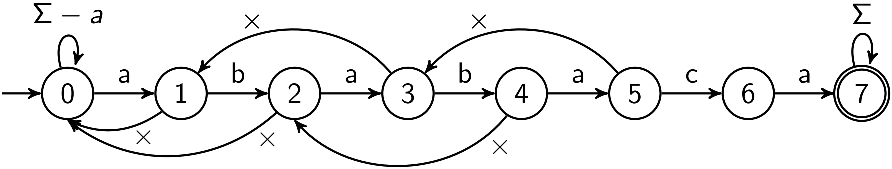
KMP failure function – fast computation



Parse $P[1..m-1]$ = babaca while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5						
$P[i]$		b		a		b		a		c						
$P[j]$		a		a		b		a		b						
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$						
$F[j]$			0		1		2		3							

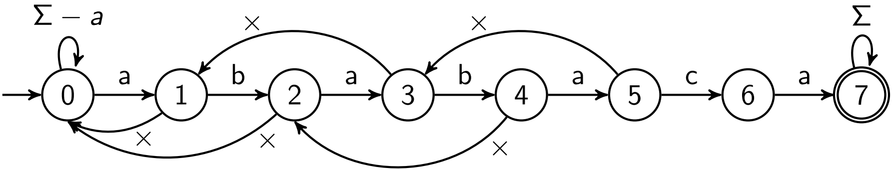
KMP failure function – fast computation



Parse $P[1..m-1]$ = babaca while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5	5						
$P[i]$		b		a		b		a		c							
$P[j]$		a		a		b		a		b							
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$	1						
$F[j]$			0		1		2		3								

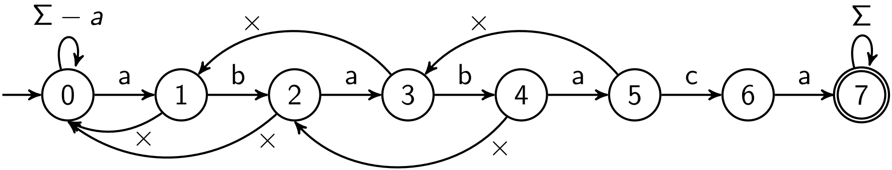
KMP failure function – fast computation



Parse $P[1..m{-}1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5	5	5					
$P[i]$		b		a		b		a		c		c					
$P[j]$		a		a		b		a		b		b					
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$	1	$\xrightarrow{\times}$					
$F[j]$			0		1		2		3								

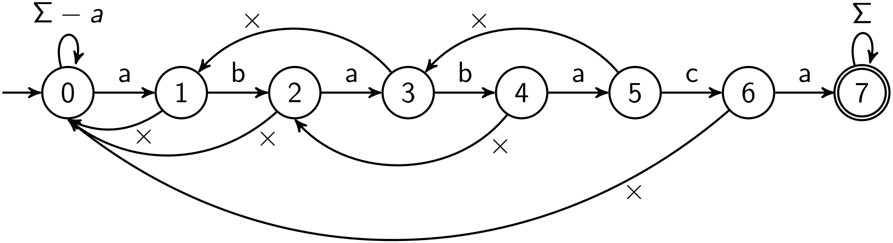
KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5	5	5	5				
$P[i]$		b		a		b		a		c		c					
$P[j]$		a		a		b		a		b		b					
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$	1	$\xrightarrow{\times}$	0				
$F[j]$			0		1		2		3								

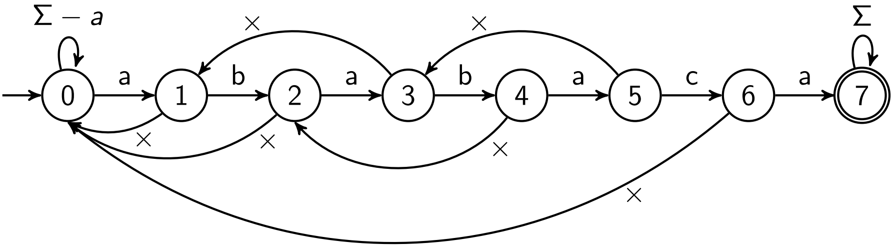
KMP failure function – fast computation



Parse $P[1..m{-}1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5	5	5	5	5	5		
$P[i]$		b		a		b		a		c		c		c			
$P[j]$		a		a		b		a		b		b		a			
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$	1	$\xrightarrow{\times}$	0	$\xrightarrow{c}$	0		
$F[j]$			0		1		2		3						0		

KMP failure function – fast computation



Parse $P[1..m-1]$ = `babaca` while adding failure-arcs:

j	1	1	1	2	2	3	3	4	4	5	5	5	5	5	5	6	6
$P[i]$		b		a		b		a		c		c		c		a	
$P[j]$		a		a		b		a		b		b		a		a	
ℓ	0	$\xrightarrow{b}$	0	$\xrightarrow{a}$	1	$\xrightarrow{b}$	2	$\xrightarrow{a}$	3	$\xrightarrow{\times}$	1	$\xrightarrow{\times}$	0	$\xrightarrow{c}$	0	$\xrightarrow{a}$	1
$F[j]$			0		1		2		3						0		1

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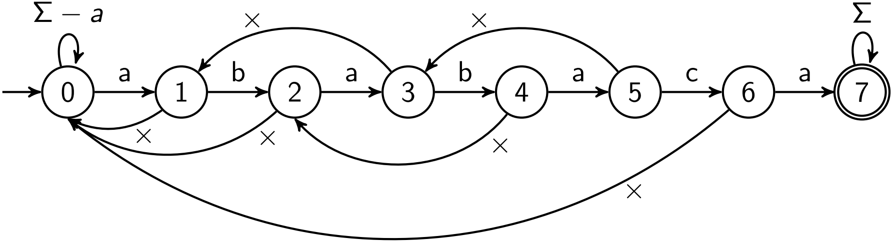
   - KMP failure function – fast computation
   - KMP failure function – improvement
   - Good suffix array

KMP failure function – improvement

We can define an even better failure-function:



Consider failure-arc from state 4:

KMP failure function – improvement

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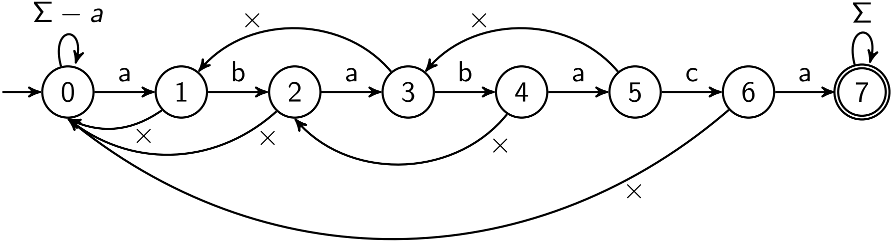

Consider failure-arc from state 4:

- This will be used if $T[i] \neq a = P[4]$ and leads to state 2.

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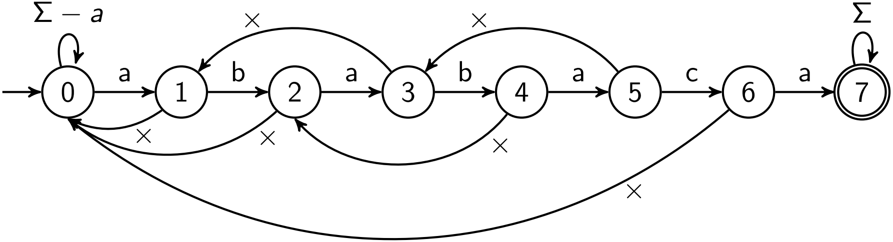

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- This will be used if $T[i] \neq a = P[4]$ and leads to state 2.
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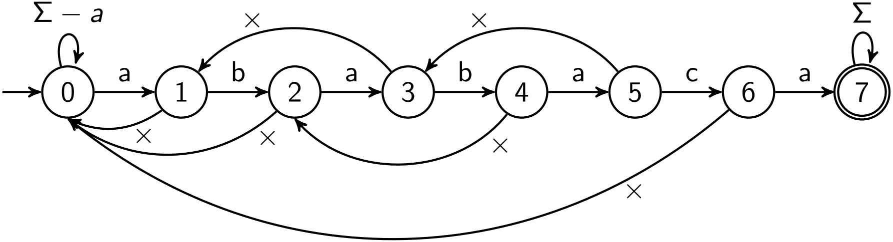

Consider failure-arc from state 4:

- This will be used if $T[i] \neq a = P[4]$ and leads to state 2.
- The next check will again compare $T[i]$ to $a = P[2]$.
- This *must* fail, and the failure-arc will lead to state 0.

KMP failure function – improvement

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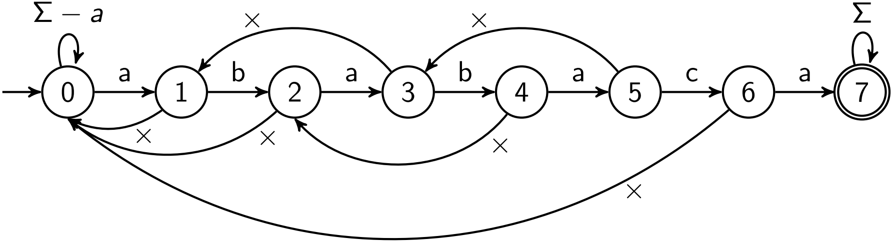
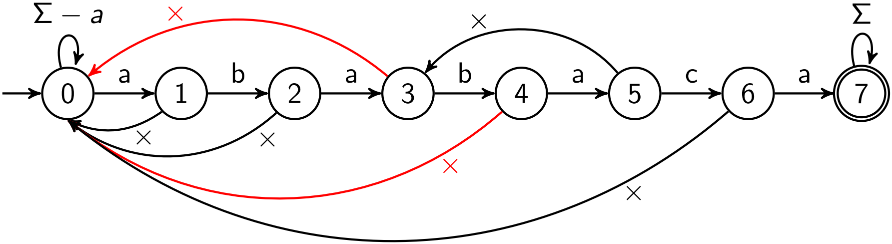


Consider failure-arc from state 4:

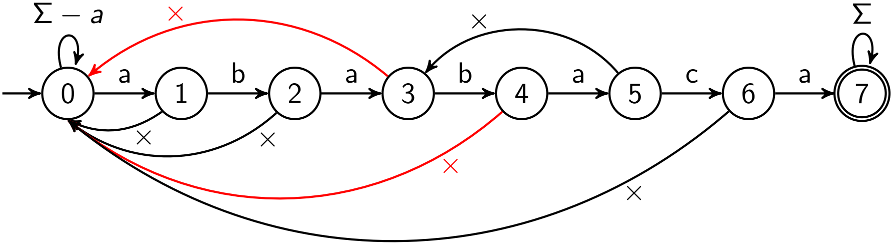
- This will be used if $T[i] \neq a = P[4]$ and leads to state 2.
- The next check will again compare $T[i]$ to $a = P[2]$.
- This *must* fail, and the failure-arc will lead to state 0.
- We might as well have gone to state 0 directly.

KMP failure function – improvement



$$F^+[j] = \begin{cases} \text{length } \ell \text{ of the longest prefix of } P \text{ that is a suffix of } P[1..j] \\ \qquad\qquad\qquad\qquad \textbf{and where } \mathbf{P}[\ell] \neq \mathbf{P}[\mathbf{j}+\mathbf{1}]. \\ 0 \text{ if no such } \ell \text{ exists} \end{cases}$$

KMP failure function – improvement



$$F^+[j] = \begin{cases} \text{length } \ell \text{ of the longest prefix of } P \text{ that is a suffix of } P[1..j] \\ \qquad\qquad\qquad\qquad \textbf{and where } \mathbf{P}[\ell] \neq \mathbf{P}[\mathbf{j}+\mathbf{1}]. \\ 0 \text{ if no such } \ell \text{ exists} \end{cases}$$

Easy to compute: $F^+[j] = \begin{cases} F[j] & \text{if } P[j+1] \neq P[F[j]] \text{ or } F[j]=0 \\ F^+[F[j]-1] & \text{otherwise} \end{cases}$

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Good suffix array - example

$P =$onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												

Good suffix array - example

P =onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	…	…
			b	o	b	o												

- Do smallest shift so that obo fits in the new guess

Good suffix array - example

P =onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	…	…
			b	o	b	o												
				(o)	(b)	(o)												

- Do smallest shift so that obo fits in the new guess

Good suffix array - example

$P =$onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												
				(o)	(b)	(o)	b	o										

- Do smallest shift so that obo fits in the new guess
- Do smallest shift so that matched suffix fits in the new guess

Good suffix array - example

$P =$onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												
				(o)	(b)	(o)	b	o										
								(o)		o								

- Do smallest shift so that obo fits in the new guess
- Do smallest shift so that matched suffix fits in the new guess
- No suffix matched $\rightsquigarrow$ shift over by one

Good suffix array - example

$P =$onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												
				(o)	(b)	(o)	b	o										
								(o)		o								
										[b]	o							

- Do smallest shift so that obo fits in the new guess
- Do smallest shift so that matched suffix fits in the new guess
- No suffix matched $\rightsquigarrow$ shift over by one (or by last-char heuristic)

Good suffix array - example

$P =$onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												
				(o)	(b)	(o)	b	o										
								(o)		o								
										[b]	o							
											[n]	(o)	b	o	b	o		

- Do smallest shift so that obo fits in the new guess
- Do smallest shift so that matched suffix fits in the new guess
- No suffix matched $\rightsquigarrow$ shift over by one (or by last-char heuristic)

Good suffix array - example

P =onobobo

n	o	o	o	b	o	o	o	o	o	b	n	b	b	o	b	o	...	...
			b	o	b	o												
				(o)	(b)	(o)	b	o										
								(o)		o								
										[b]	o							
											[n]	(o)	b	o	b	o		

- Do smallest shift so that obo fits in the new guess
- Do smallest shift so that matched suffix fits in the new guess
- No suffix matched ⇝ shift over by one (or by last-char heuristic)
- What to do if the matched part does not repeat?

Good suffix array - if matched part doesn't repeat

$P =$ nbonnnbo (different from before)

n	b	b	n	n	n	b	o	o	n	n	b	o	b	b	o	b	o	...	...
		o	n	n	n	b	o												

- Cannot match all of nnnbo

Good suffix array - if matched part doesn't repeat

$P =$nbonnnbo (different from before)

n	b	b	n	n	n	b	o	o	n	n	b	o	b	b	o	b	o	...	...
		o	n	n	n	b	o												
					(n)	(b)	(o)												

- Cannot match all of nnnbo
- But nbo fits a prefix of P $\rightsquigarrow$ shift to that guess

Good suffix array - if matched part doesn't repeat

$P =$nbonnnbo (different from before)

n	b	b	n	n	n	b	o	o	n	n	b	o	b	b	o	b	o	...	...
		o	n	n	n	b	o												
					(n)	(b)	(o)	n	n	n	b	o							
										(n)	(b)	(o)							

- Cannot match all of nnnbo
- But nbo fits a prefix of P $\rightsquigarrow$ shift to that guess
- Generally: Re-use longest suffix of matched part that fits a prefix of P

Good suffix array - if matched part doesn't repeat

$P =$nbonnnbo (different from before)

n	b	b	n	n	n	b	o	o	n	n	b	o	b	b	o	b	o	…	…
		o	n	n	n	b	o												
					(n)	(b)	(o)	n	n	n	b	o							
										(n)	(b)	(o)			n	b	o		

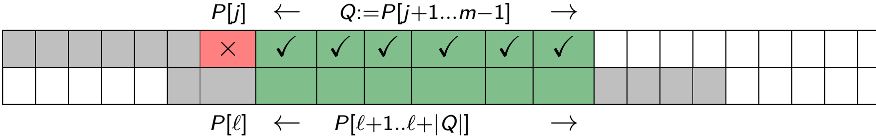
- Cannot match all of nnnbo
- But nbo fits a prefix of $P \rightsquigarrow$ shift to that guess
- Generally: Re-use longest suffix of matched part that fits a prefix of P
- If nothing fits: Shift guess all the way past previous guess.

$P =$nobnnnbo (different from before)

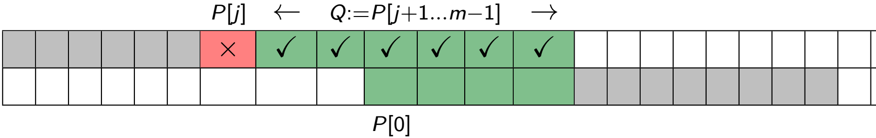
n	b	b	n	n	n	b	o	o	n	n	b	o	b	b	o	b	o	…	…
		o	n	n	n	b	o												

Definition of good suffix array

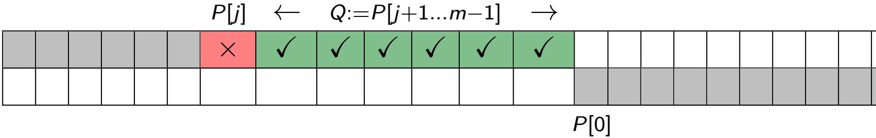
- Assume search failed at $P[j]$, but had matched $P[j+1..m-1] =: Q$
- Case 1: Q appears as substring of P elsewhere



- Case 2: A suffix of Q is a prefix of P.

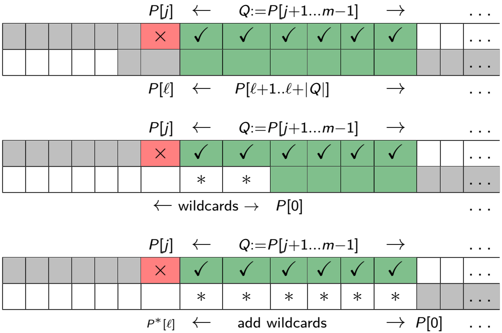


- Case 3: Neither (i.e., only empty suffix fits).



Definition of good suffix array

- Can unify all three cases into one!
- Let P^* be P with m *wildcards* attached in front.



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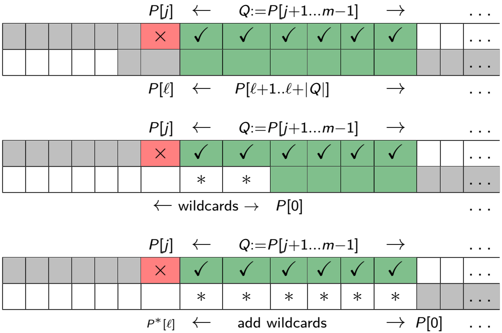

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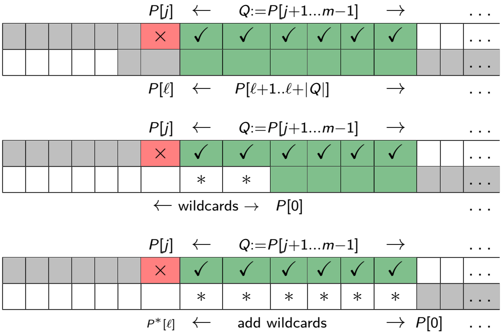

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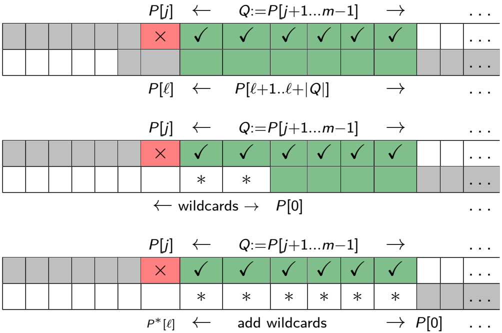

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- So Q is prefix of $P^*[\ell{+}1...m{-}1]$
- Want $\ell \neq j$ so that we actually shift

$$S[j] = \max_{\ell \neq j} \quad P[j{+}1..m{-}1] \textbf{ is a prefix of } P^*[\ell{+}1..m{-}1]$$

Good Suffix Array Computation - human

$$
\begin{aligned}
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&= \max_{\ell} \quad P[j{+}1..m{-}1] \text{ is a prefix of } P^*[\ell{+}1..m{-}2]
\end{aligned}
$$

$P =$ boobobo		$P^*[-m..m-2]$														
		-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5		
j	$P[j{+}1..m{-}1]$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	b	o	o	b	o	b	$\ell+1$	$S[j]$
5	o												o		4	3
4	bo											b	o		3	2
3	obo										o	b	o		2	1
2	bobo						b	o	b	o					-2	-3
1	obobo					o	b	o	b	o					-3	-4
0	oobobo				o	o	b	o	b	o					-4	-5

Easy to compute in polynomial time:

- Write down P^*, omitting rightmost character.
- For each j, write down $P[j{+}1..m{-}1]$
- Find rightmost match $\rightsquigarrow$ gives $\ell+1$ $\rightsquigarrow$ gives $S[j]$

Good Suffix Array Computation - computer

Idea: After reformulations, this resembles the KMP failure function!

$$S[j] = \max_{\ell \neq j}\{\ P[j{+}1..m{-}1] \text{ is a prefix of } P^*[\ell{+}1..m{-}1]\ \}$$

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(define R to be reverse of P^*: $R[j] = P^*[m{-}1{-}j]$)

$$= \max_{\ell}\{ \; R[0..m{-}j{-}2] \text{ is a suffix of } R[1..m{-}\ell{-}2] \; \}$$

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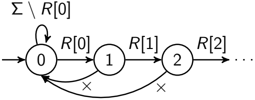
(define R to be reverse of P^*: $R[j] = P^*[m{-}1{-}j]$)

$$= \max_{\ell}\{\ \underbrace{R[0..m{-}j{-}2]}_{\text{prefix of } R} \text{ is a suffix of } R[1..\underbrace{m{-}\ell{-}2}_{k}]\ \}$$

$$= m - 2 - \min_{k}\{\ \text{the } (m{-}j{-}1)^{\text{st}} \text{ prefix of } R \text{ is a suffix of } R[1..k]\ \}$$

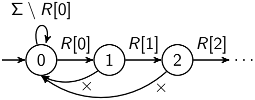
This should remind you of properties of a KMP-automaton.

Good Suffix Array Computation - computer

Recall KMP-automaton for R: 

We reach state q if the q^{th} prefix of R was a suffix of what was parsed.

Good Suffix Array Computation - computer

Recall KMP-automaton for R: 

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$$S[j] \;=\; m-2-\min_{k}\{\text{ the } (m-j-1)^{\text{st}} \text{ prefix of } R \text{ is a suffix of } R[1..k]\ \}$$

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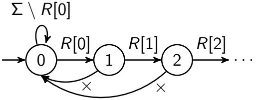

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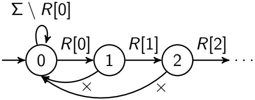
Recall KMP-automaton for R: 

We reach state q if the q^{th} prefix of R was a suffix of what was parsed.

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$$=\; m{-}2{-}\min_k\{\text{ state } \underbrace{m{-}j{-}1}_{q} \text{ is reached when } \underbrace{\text{parsing}}_{\text{on KMP-automaton for } R}\ R[1..k]\ \}$$

$$S[m{-}q{-}1] \;=\; m{-}2{-}\min_k\{\text{ state } q \text{ reached when parsing } R[1..k]\ \}$$

Good Suffix Array Computation - computer

Final result:

$$S[m-q-1] \quad = \quad m-2-\min_k \left\{ \begin{array}{l} \text{parsing } R[1..k] \text{ on the KMP-automaton for} \\ R = P^{\text{reverse}} *** \ldots * \text{ brings us to state } q \end{array} \right\}$$

Good Suffix Array Computation - computer

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So to compute $S[\cdot]$:

- Create KMP-automaton $\mathcal{K}_R$ for $R := P^{\text{reverse}} {*}{*}{*} \ldots {*}$
- Parse $R[1..2m-1]$ on $\mathcal{K}_R$
- Whenever we reach a state q
  - Check whether q was visited already
  - If not: $S[m-q-1] \leftarrow m-2-k$, where $R[k]$ is last parsed character.

Run-time: $O(m)$ since R has $O(m)$ characters.