Pattern Matching

Pattern Matching

- Given
  - a word w (the text) of length n, and
  - a regular expression p (the pattern) of length m

  determine
  - the smallest number k' such that some $[k, k']$-factor of w belongs to $L(p)$.

NFA-based solution

PatternMatchingNFA(t, p)
Input: text $t = a_1 \ldots a_n \in \Sigma^+$, pattern $p \in \Sigma^*$
Output: the first occurrence of p in t, or $\perp$ if no such occurrence exists.

```
1  A ← RegtoNFA(Σ* p)
2  S ← Q_0
3  for all k = 0 to n − 1 do
4      if S ∩ F ≠ ∅ then return k
5      S ← δ(S, a_{k+1})
6  return ⊥
```

- Line 1 takes $O(m^3)$ time ($O(m^2)$ for fixed alphabet) , output has $O(m)$ states
- Loop is executed at most n times
- One iteration takes $O(s^2)$ time , where s is the number of states of A
- Since $s = O(m)$, the total runtime is $O(m^3 + nm^2)$, and $O(nm^2)$ for $m \leq n$.

DFA-based solution

PatternMatchingDFA(t, p)

Input: text $t = a_1 \ldots a_n \in \Sigma^+$, pattern p

Output: the first occurrence of p in t, or $\perp$ if no such occurrence exists.

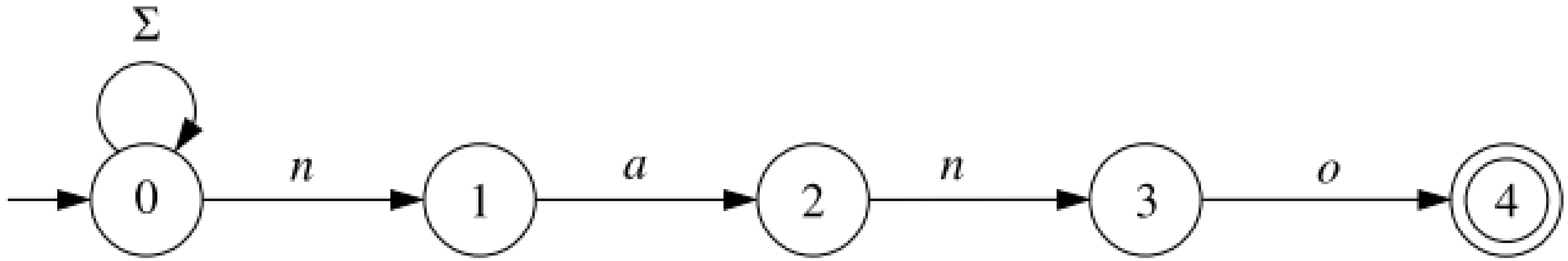
```
1  A ← NFAtoDFA(RegtoNFA(Σ* p))
2  q ← q0
3  for all k = 0 to n − 1 do
4      if q ∈ F then return k
5      q ← δ(q, a_{k+1})
6  return ⊥
```

- Line 1 takes $2^{O(m)}$ time
- Loop is executed at most n times
- One iteration takes constant time
- Total runtime is $O(n) + 2^{O(m)}$

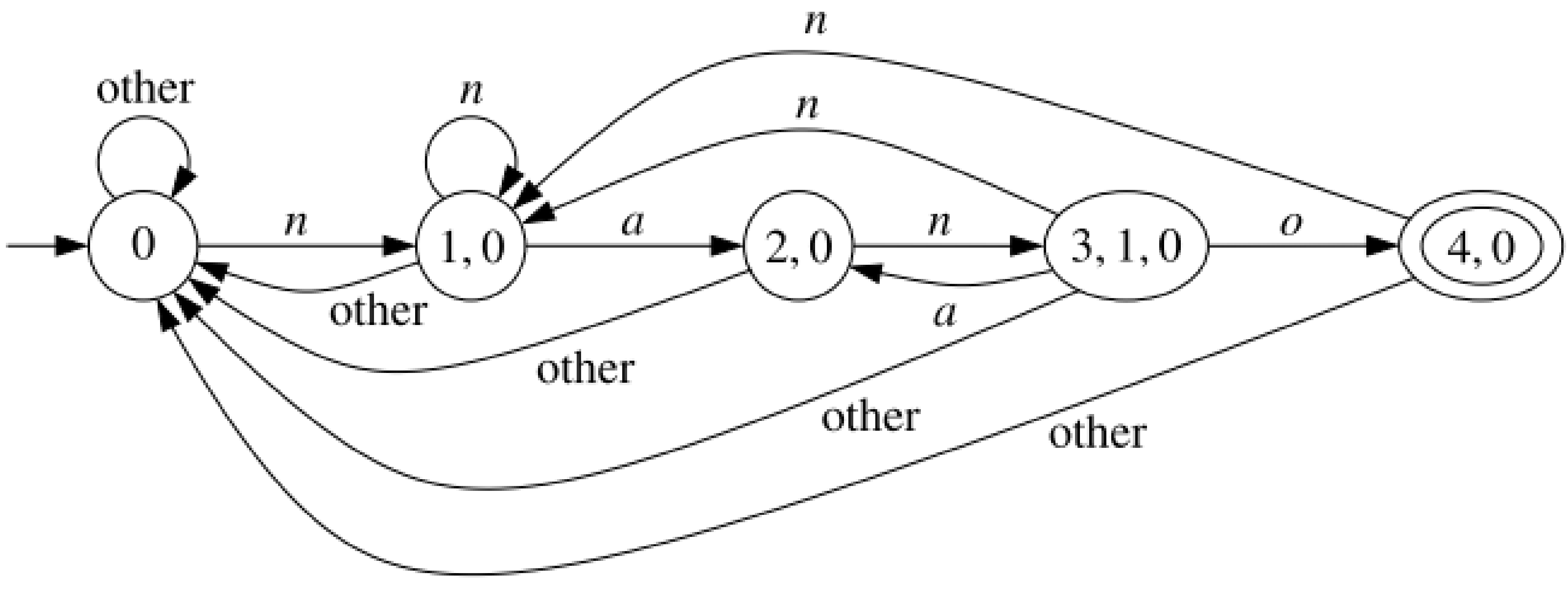
The word case

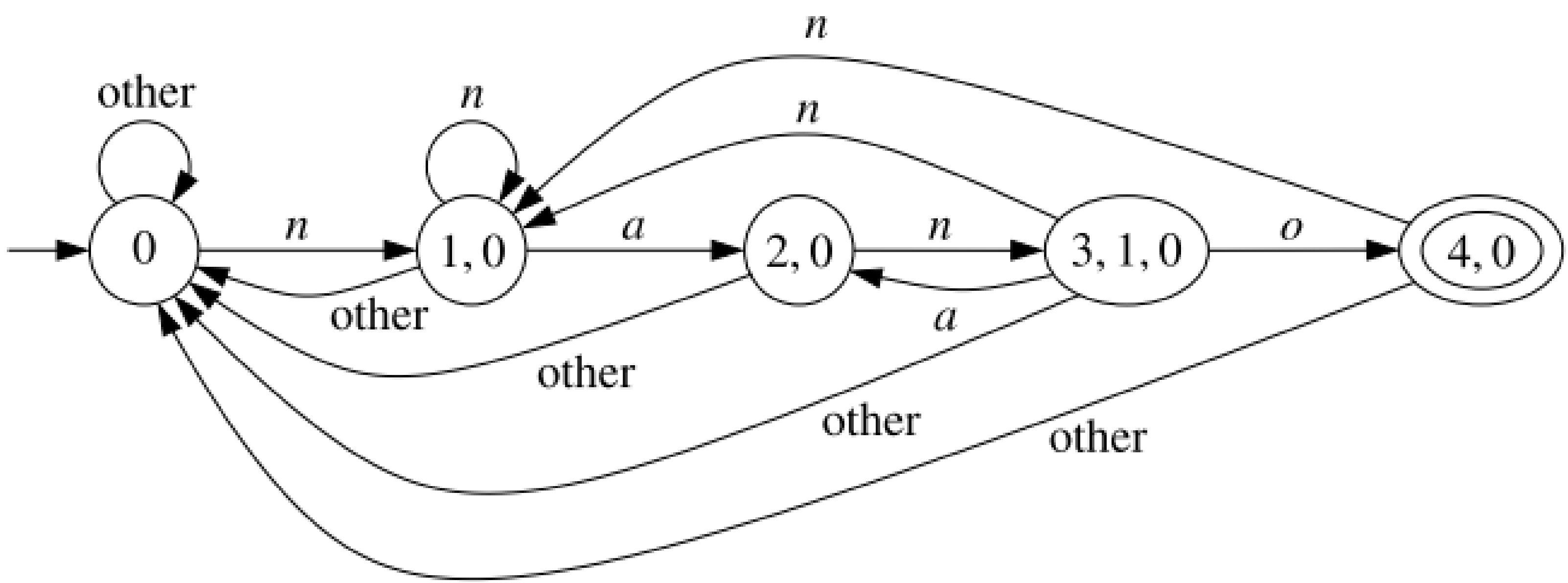
- The pattern $p = b_1 b_2 \dots b_m$ is a word of length m
- Naive algorithm: move a window of size m along the word one letter at a time, and compare with p after each step. Runtime: $O(nm)$
- We give an algorithm with $O(n + m)$ runtime for any alphabet of size $0 \leq |\Sigma| \leq n$.
- First we explore in detail the shape of the DFA for $\Sigma^* p$.

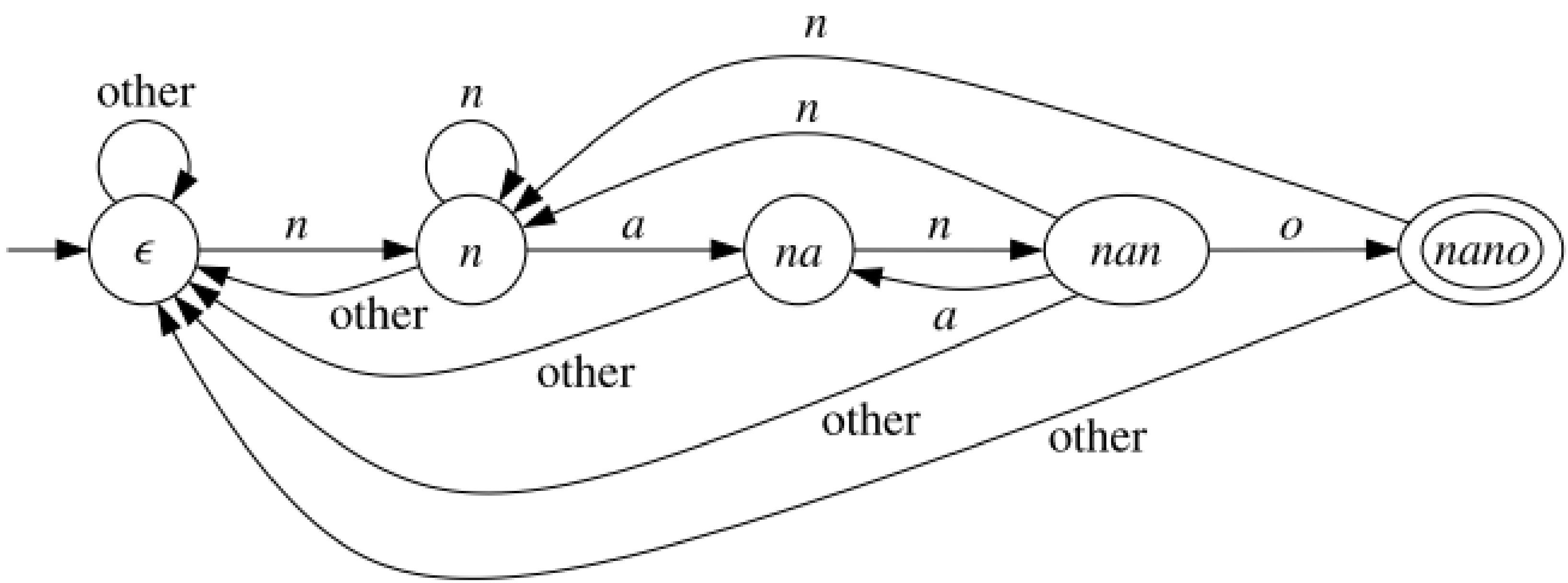
Obvious NFA for $\Sigma^* p$ and $p = nano$



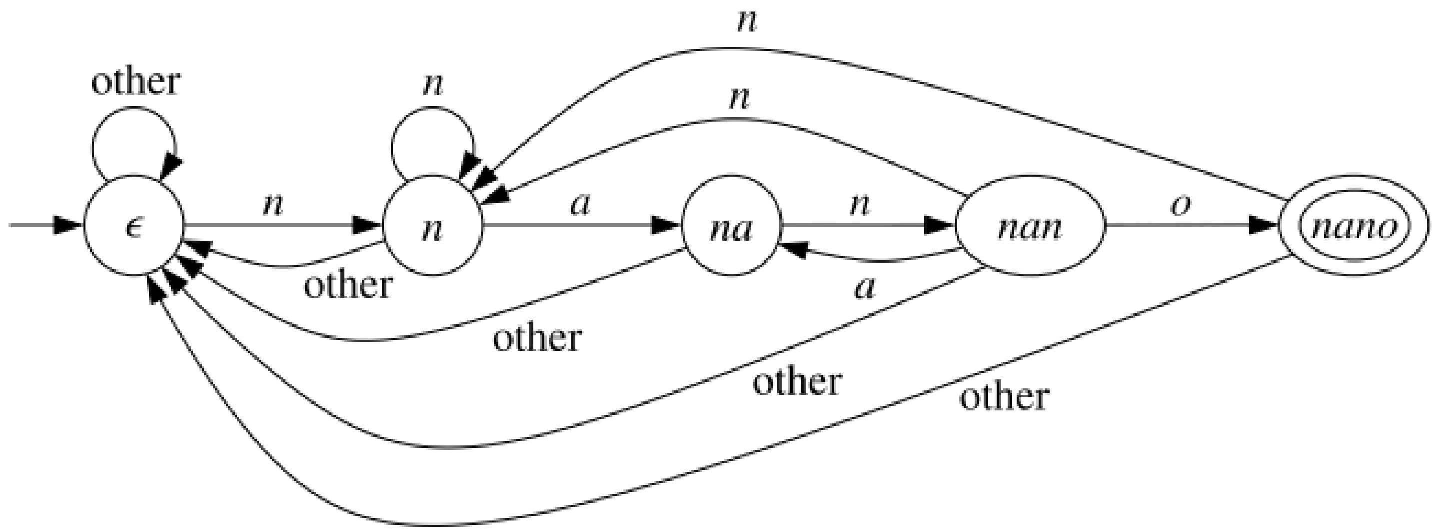
Result of applying NFAtoDFA:




0
1, 0
2, 0
3, 1, 0
4, 0
n
a
o
other

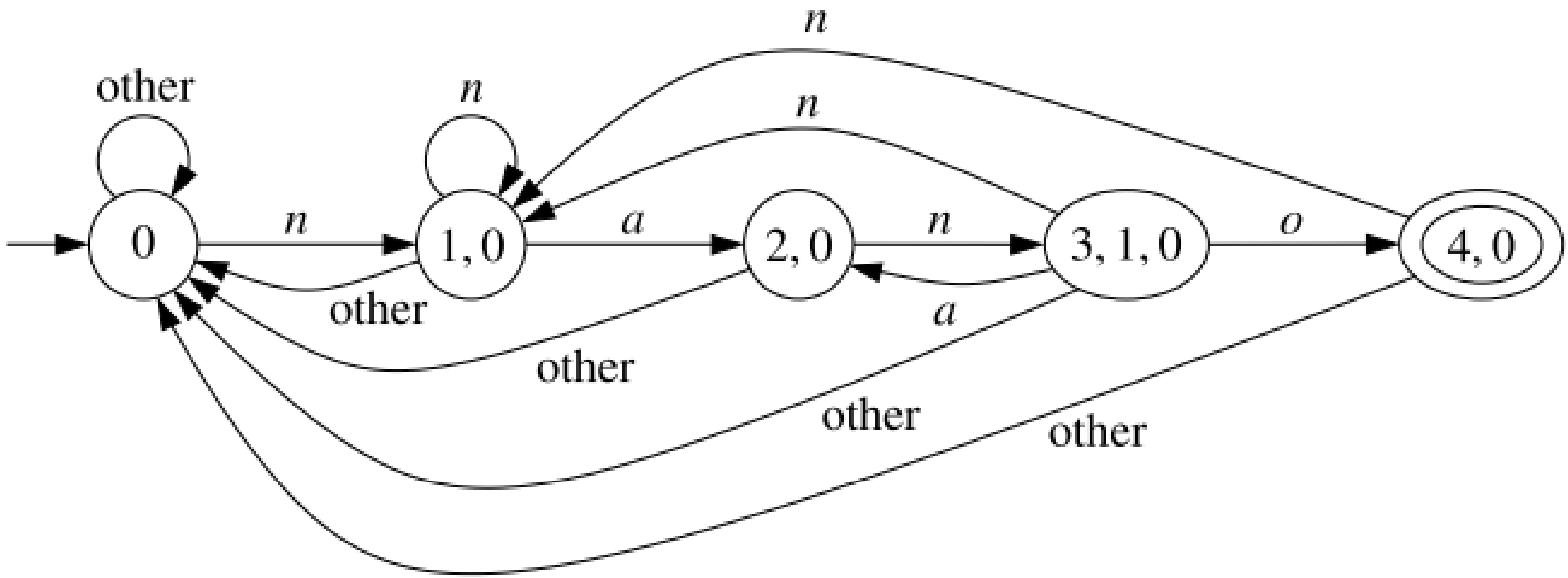

ϵ
n
na
nan
nano
a
o
other

Intuition



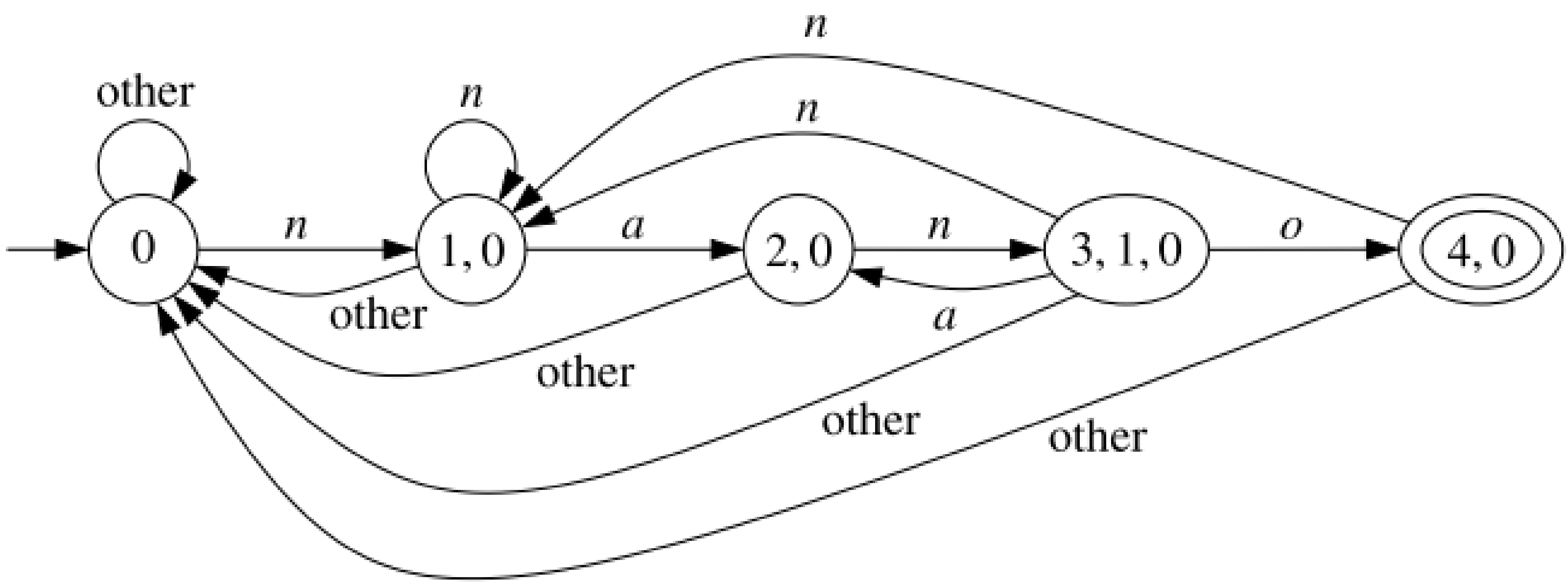
- Transitions of the „spine“ correspond to hits: the next letter is the one that „makes progress“ towards nano
- Other transitions correspond to misses, i.e., „wrong letters“ and „throw the automaton back“

Observations



- For every state $i = 0,1, \dots, 4$ of the NFA there is exactly one state S of the DFA such that i is the largest state of S.
- For every state S of the DFA, with the exception of $S = \{0\}$, the result of removing the largest state is again a state of the DFA.

Observations



- For every state $i = 0,1,\dots,4$ of the NFA there is exactly one state S of the DFA such that i is the largest state of S.
- For every state S of the DFA, with the exception of $S = \{0\}$, the result of removing the largest state is again a state of the DFA.
- Do these properties hold for every pattern p?

Heads and tails, hits and misses

- Head of S, denoted $h(S)$: largest state of S
- Tail of S, denoted $t(S)$: rest of the state
- Example: $h(\{3,1,0\}) = 3$, $t(\{3,1,0\}) = \{1,0\}$

- Given a state S, the letter leading to the next state in the „spine“ is the (unique) hit letter for S
- All other letters are miss letters for S
- Example: hit for $\{3,1,0\}$ is o, whereas n or a are misses

Fundamental property of the DFA

- Proposition: Let S_k be the k-th state picked from the workset during the execution of *NFAtoDFA(A_p)*.

  (1) $h(S_k) = k$,

  (2) If $k > 0$, then $t(S_k) = S_l$ for some $l < k$

Proof Idea:

- (1) and (2) hold for $S_0 = \{0\}$.
- For the step $k \to k+1$ we look at $\delta(S_k, a)$ for each a, where δ transition relation of A_p .
- By i.h. we have $S_k = \{k\} \cup S_l$ for some $l < k$
- We distinguish two cases: a is a hit for S_k (that is, $a = b_{k+1}$), and a is a miss for S_k .

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Hit:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ \Big\downarrow a & & \Big\downarrow a \\ \{k+1\} & \cup & \delta(S_l, a) \end{array}$$

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Hit:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ a\Big\downarrow & & a\Big\downarrow \\ \{k+1\} & \cup & \delta(S_l, a) \end{array}$$

Added earlier to the workset, and so some $S_{l'}$

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Hit:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ a\downarrow & & a\downarrow \\ \{k+1\} & \cup & \delta(S_l, a) \\ = & & = \\ \{k+1\} & \cup & S_{l'} \end{array}$$

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Hit:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ \Big\downarrow a & & \Big\downarrow a \\ \{k+1\} & \cup & \delta(S_l, a) \\ = & & = \\ \{k+1\} & \cup & S_{l'} \end{array}$$

New state, gets added to the workset

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Miss:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ \Big\downarrow a & & \Big\downarrow a \\ \emptyset & \cup & \delta(S_l, a) \end{array}$$

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Miss:

$$\begin{array}{ccc} \{k\} & \cup & S_l \\ a\big\downarrow & & a\big\downarrow \\ \emptyset & \cup & \delta(S_l, a) \\ & & = \\ & & S_{l'} \end{array}$$

- $S_k = \{k\} \cup S_l$ for some $l < k$
- $\delta(S_k, a) = \delta(k, a) \cup \delta(S_l, a)$

Miss:

$$
\begin{tikzcd}
\{k\} \arrow[d, "a"'] & \cup & S_l \arrow[d, "a"'] \\
\emptyset & \cup & \delta(S_l, a) \\
 & & = \\
 & & S_{l'}
\end{tikzcd}
$$

Already seen, is not added to the workset

Consequences

Prop: The result of applying *NFAtoDFA*(A_p), where A_p is the obvious NFA for $\Sigma^* p$, yields a minimal DFA with $m + 1$ states and $|\Sigma|(m + 1)$ transitions.

Proof: All states of the DFA accept different languages.

So: concatenating *NFAtoDFA and PatternMatchingDFA* yields a $O(n + |\Sigma| m)$ algorithm.

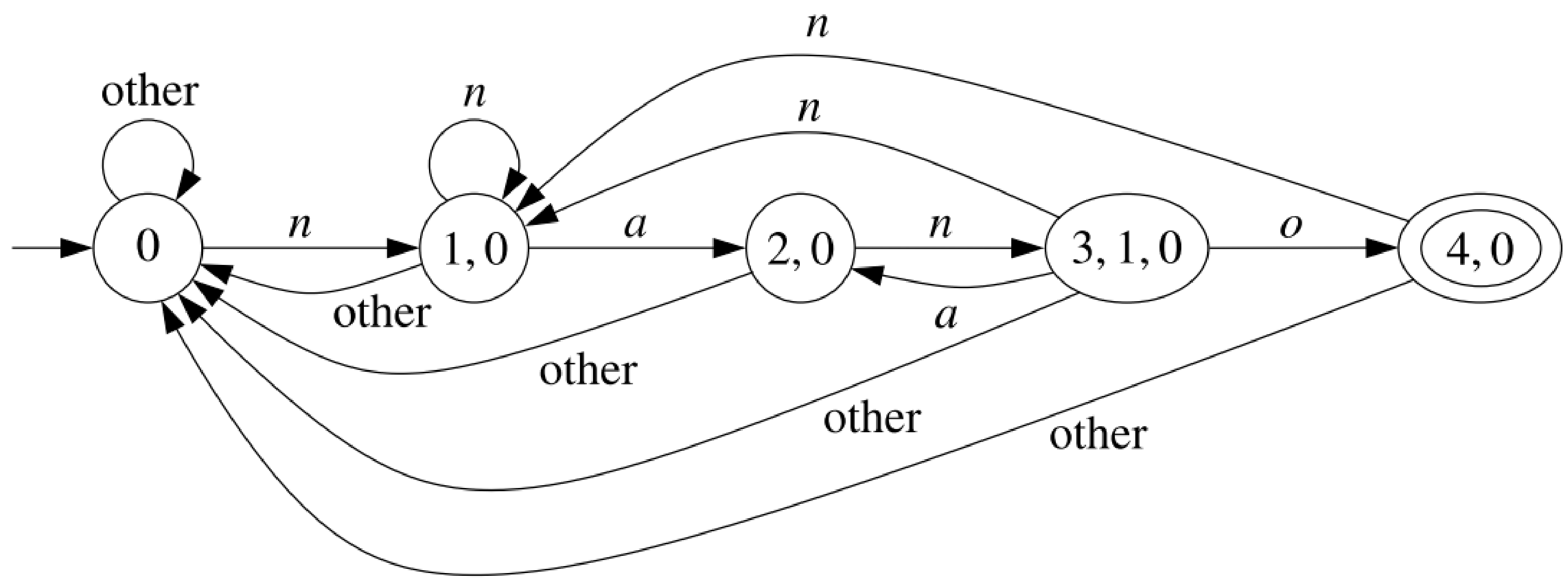
- Good enough for constant alphabet
- Not good enough for $|\Sigma| = \Omega(n)$

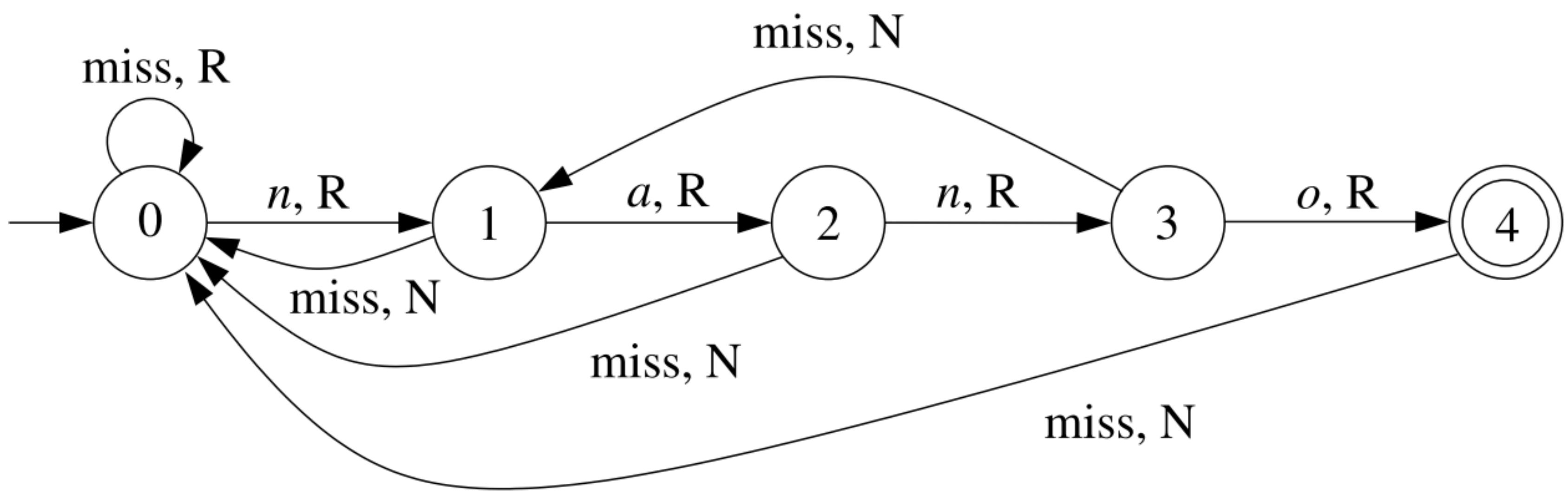
Lazy DFAs

- We introduce a new data structure: lazy DFAs. We construct a lazy DFA for $\Sigma^* p$ with $m + 1$ states and $2m + 2$ transitions.
- Lazy DFAs: automata that read the input from a tape by means of a reading head that can move one cell to the right or stay put
- DFA=Lazy DFA whose head never stays put

Lazy DFA for $\Sigma^* p$

- By the fundamental property, the DFA B_p for $\Sigma^* p$ behaves from state S_k as follows:
  - If a is a hit, then $\delta_B(S_k, a) = S_{k+1}$, i.e., the DFA moves to the next state in the spine.
  - If a is a miss, then $\delta_B(S_k, a) = \delta_B(t(S_k), a)$, i.e., the DFA moves to the same state it would move to if it were in state $t(S_k)$.
- When a is a miss for S_k, the lazy automaton moves to state $t(S_k)$ without advancing the head. In other words, it „delegates“ doing the move to $t(S_k)$
- So the lazyDFA behaves the same for all misses.


other
n
n
n
0
n
1, 0
a
2, 0
n
3, 1, 0
o
4, 0
other
a
other
other
other
other


miss, N
miss, R
0
n, R
1
a, R
2
n, R
3
o, R
4
miss, N
miss, N
miss, N

- Formally, for the lazy DFA C:
  - $\delta_C(S_k, a) = (S_{k+1}, R)$ if a is a hit
  - $\delta_C(S_k, a) = (t(S_k), N)$ if a is a miss
- So the lazy DFA has $m + 1$ states and $2m$ transitions.
- It can be constructed in $O(m)$ space:
  - For each $0 \leq k \leq n$, compute and store S_k with
    - $S_0 \coloneqq \{0\}$, and
    - $S_{k+1} \coloneqq \delta_A(S_k, b_{k+1})$,
  - Compute the transitions as at the top of the slide.

- Running the lazy DFA on the text takes $O(n)$ time:
  - For every text letter the lazy DFA performs a sequence of „stay put“ steps followed by a „right“ step. Call this sequence a macrostep.
  - Let S_{j_i} be the state after the i-th macrostep. The number of steps of the i-th macrostep is at most $j_{i-1} - j_i + 2$.

  So the total number of steps is at most

$$\sum_{i=1}^{n} (j_{i-1} - j_i + 2) = j_0 - j_n + 2n \leq 2n$$

Computing the lazy DFA in $O(m)$ time

- For the $O(m + n)$ bound it remains to show that the lazy DFA can be constructed in $O(m)$ time.
- Let $Miss(k)$ be the head of the state reached from S_k by a miss.
- It is easy to compute each of $Miss(0), \dots, Miss(m)$ in $O(m)$ time, leading to a $O(n + m^2)$ time algorithm.

  (Compute the S_k and use $Miss(k) = h(t(S_k))$.)
- Already good enough for almost all purposes. But, can we compute all of $Miss(0), \dots, Miss(m)$ together in time $O(m)$? Looks impossible!
- It isn‘t though ...

For $i > 1$ we have:

$$\begin{aligned}
t(S_i) &= t(\ \delta_B(S_{i-1}, b_i)\ ) \\
&= t(\delta_A(\{i-1\}, b_i) \cup \delta_A(t(S_{i-1}), b_i)) \\
&= t\Big(\ \{i\} \cup \delta_A(t(S_{i-1}), b_i)\Big) \\
&= \delta_B(t(S_{i-1}), b_i)
\end{aligned}$$

For $i > 1$ we have:

$$\begin{aligned} t(S_i) &= t(\ \delta_B(S_{i-1}, b_i)\ ) \\ &= t(\delta_A(\{i-1\}, b_i) \cup \delta_A(t(S_{i-1}), b_i)) \\ &= t\big(\ \{i\} \cup \delta_A(t(S_{i-1}), b_i)\big) \\ &= \delta_B(t(S_{i-1}), b_i) \end{aligned}$$

Define $miss(S_i) := t(S_i)$ (that is, $Miss(k) = h(miss(S_i))$).
We get:

$$miss(S_i) = \begin{cases} S_0 & \text{if } i = 0 \text{ or } i = 1 \\ \delta_B(miss(S_{i-1}), b_i) & \text{if } i > 1 \end{cases}$$

$$\delta_B(S_j, b) = \begin{cases} S_{j+1} & \text{if } b = b_{j+1} \text{ (hit)} \\ S_0 & \text{if } b \neq b_{j+1} \text{ (miss) and } j = 0 \\ \delta_B(miss(S_j), b) & \text{if } b \neq b_{j+1} \text{ (miss) and } j \neq 0 \end{cases}$$

$$
miss(S_i) = \begin{cases} S_0 & \text{if } i = 0 \text{ or } i = 1 \\ \delta_B(miss(S_{i-1}), b_i) & \text{if } i > 1 \end{cases}
$$

$$
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$$

- With $Miss(i) \coloneqq h(miss(S_i))$ we get the following algorithm:

CompMiss(p)
Input: pattern $p = b_1 \cdots b_m$.
Output: heads of targets of miss transitions.

$Miss(0) \leftarrow 0$; $Miss(1) \leftarrow 0$
for $i \leftarrow 2, \ldots, m$ **do**
    $Miss(i) \leftarrow DeltaB(\, Miss(i-1)\,,\, b_i\,)$

DeltaB(j, b)
Input: head $j \in \{0, \ldots, m\}$, letter b.
Output: head of the state $\delta_B(S_j, b)$.

while $b \neq b_{j+1}$ **and** $j \neq 0$ **do** $j \leftarrow Miss(j)$
if $b = b_{j+1}$ **then return** $j + 1$
else return 0

- Observe: the values *Miss(j)* required by each call of *DeltaB* have already been computed when they are needed.

CompMiss(p)

Input: pattern $p = b_1 \cdots b_m$.

Output: heads of targets of miss transitions.

1 $\quad Miss(0) \leftarrow 0;\ Miss(1) \leftarrow 0$

2 $\quad$ **for** $i \leftarrow 2, \ldots, m$ **do**

3 $\qquad Miss(i) \leftarrow DeltaB(\, Miss(i-1)\, ,\ b_i\,)$

DeltaB(j, b)

Input: head $j \in \{0, \ldots, m\}$, letter b.

Output: head of the state $\delta_B(S_j, b)$.

1 $\quad$ **while** $b \neq b_{j+1}$ **and** $j \neq 0$ **do** $\ j \leftarrow Miss(j)$

2 $\quad$ **if** $b = b_{j+1}$ **then return** $j + 1$

3 $\quad$ **else return** 0

All calls to *DeltaB* lead together to $O(m)$ iterations of the while loop.

The call $DeltaB(Miss(i-1), b_i)$ executes at most

$$Miss(i-1) - (Miss(i) - 1)$$

iterations, because:

- initially j is assigned $Miss(i-1)$ (line 3 of *CompMiss*)
- each iteration decreases j by at least 1 (line 1 of $DeltaB$, $Miss(j) < j$)
- the return value assigned to $Miss(i)$ is at most the final value of j plus 1. (line 2 of $DeltaB$)

- Total number of iterations:

$$\sum_{i=2}^{m}(Miss(i-1) - Miss(i) + 1)$$

$$\leq \; Miss(1) - Miss(m) + m - 1$$

$$\leq m$$