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Algorithmen auf Sequenzen

Exakte Mustersuche mit mehreren Mustern

Sven Rahmann

Genominformatik
Universitätsklinikum Essen
Universität Duisburg-Essen
Universitätsallianz Ruhr

Einführung

- Problem der exakten Mustersuche für mehrere Muster gleichzeitig
- Anwendung: “Naive” Fehlertoleranz, z.B. {Maier, Mayer, Meier, Meyer}.
- Sei $P := \{P_1, \ldots, P_k\}$
- Sei $m_i := |P_i|$ für $1 \leq i \leq k$; $m := \sum_i m_i$ (Gesamtlänge)

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- Sei $m_i := |P_i|$ für $1 \leq i \leq k$;
  $m := \sum_i m_i$ (Gesamtlänge)
- Einfache Lösung: Algorithmus für ein Muster (z.B. KMP)
  k-mal anwenden, $\mathcal{O}(m + kn)$ Zeit
- Gewünscht: $\mathcal{O}(m + n + z)$ Zeit; dabei z: Ausgabegröße

Zählweise der Treffer

Anzahl der Treffer von P in Text T kann auf (mindestens) drei verschiedene Arten gezählt werden:

1. Überlappende Treffer; entspricht Anzahl der Paare (i, j) mit $T[i : j] \in P$ (Standard-Definition).

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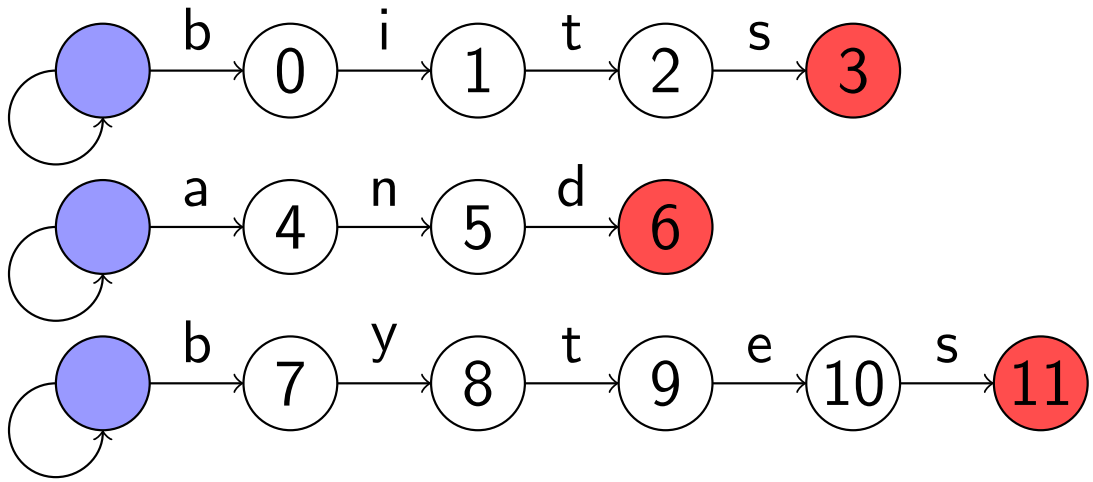
2. Endpositionen von Treffern; entspricht Anzahl der j, für die es mindestens ein i gibt mit $T[i : j] \in P$.
3. Nichtüberlappende Treffer; gesucht ist eine maximale Menge von Paaren (i, j) mit $T[i : j] \in P$, so dass die Intervalle $[i : j]$ paarweise disjunkt sind.

Shift-And-Algorithmus auf Mengen



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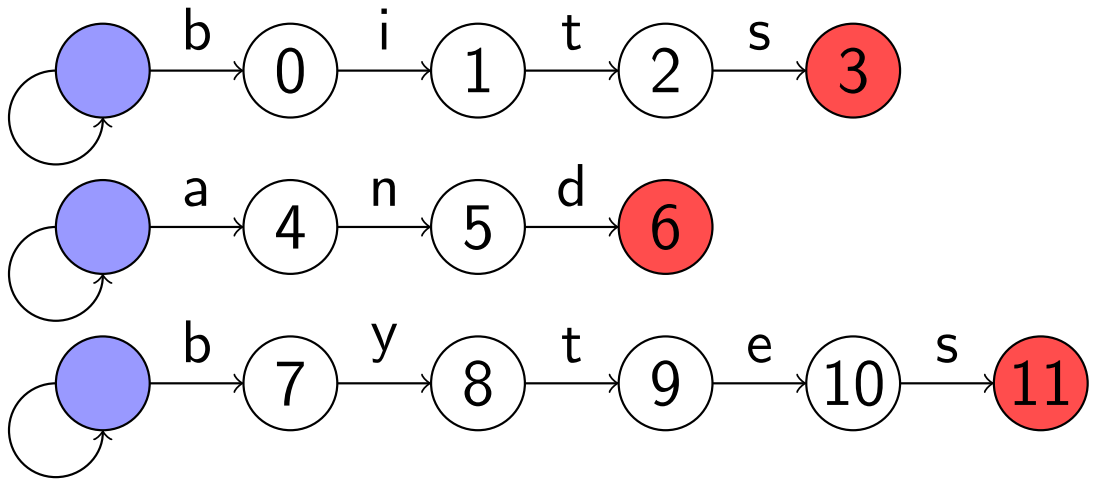

- NFA zum Finden der Wörter aus der Menge {bits, and, bytes}.
- Startzustände: blau; akzeptierend: rot
- Obwohl es mehrere Zusammenhangskomponenten gibt, handelt es sich um **einen** Automaten.

Shift-And-Algorithmus auf Mengen

- NFA, der $\Sigma^* P = \bigcup_{i=1}^{k} \Sigma^* P_k$ akzeptiert.
- Zustandsmenge $Q := \{(i, j) \mid 1 \leq i \leq k, -1 \leq j < |P_i|\}$.
- Zustand (i, j) repräsentiert Präfix $P_i[..j]$ mit $P_i \in P$.

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- Zustand (i,j) repräsentiert Präfix $P_i[..j]$ mit $P_i \in P$.
- Sei $Q_0 = \{(i,-1) \mid 1 \leq i \leq k\}$ die Menge der Zustände, die das leere Präfix repräsentieren (Startzustände).
- Sei $T = \{(i,|P_i|-1) \mid 1 \leq i \leq k\}$ die Menge der Zustände, die jeweils ein Muster repräsentieren (Endzustände).
- Übergang von (i,j) nach $(i,j+1)$ durch Lesen von $P_i[j+1]$

Der Shift-And-Algorithmus auf Mengen

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Implementierung:

- Alle Muster werden zu einem Muster konkateniert, $P \mapsto \texttt{bitsandbytes}$.
- Die Startzutände werden in einem Bitfeld A_0 gespeichert, $A_0[j] := 1$, wenn $j \in \{\sum_{i=1}^{g} |P_i| \mid 0 \leq g < k\}$.
  Hier $A_0 = \texttt{000010010001}$.
- Die akzeptierenden Zustände werden ebenfalls in einem Bitfeld gespeichert,
  $accept[j] := 1$, wenn $j \in \{\sum_{i=1}^{g} |P_i| - 1 \mid 1 \leq g \leq k\}$.
  Hier $accept = \texttt{100001001000}$.

Der Shift-And-Algorithmus auf Mengen

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Erstellung der Masken:

```
1  def create_masks(Ps, S):
2      mask = {s: 0 for s in S}
3      A_0, accept, bit = 0, 0, 1
4      for p in Ps:
5          A_0 |= bit
6          for c in p:
7              mask[c] |= bit
8              bit <<= 1
9          accept |= bit
10     return mask, A_0, accept >> 1
```

Der Shift-And-Algorithmus auf Mengen

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Mustersuche mit dem Shift-And-Algorithmus:

```
1 def shift_and_multi(Ps, T):
2     S, A = set("".join(Ps) + T), 0
3     mask, A_0, accept = create_masks(Ps, S)
4     for i, c in enumerate(T):
5         A = ((A << 1) | A_0) & mask[c]
6         if A & accept:
7             yield i
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Der Shift-And-Algorithmus auf Mengen

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In diesem Code wird nur die Endposition eines Matches übergeben. Will man zusätzlich die Startposition kennen, so muss erkannt werden, welche akzeptierenden Zustände aktiv sind.

Zusammenfassung

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- Der Shift-And-Algorithmus lässt sich problemlos auf eine Menge von Mustern erweitern, solange die Gesamtlänge aller Muster kleiner als die Registergröße ist.
- Die Laufzeit beträgt $\mathcal{O}(m + n\lceil m/W \rceil)$.
- Es wird nur berichtet, an welchen Textpositionen mindestens ein Muster endet.

KMP auf Mengen: Aho-Corasick

- Jedes Muster mit KMP suchen: Zeit $\mathcal{O}(kn + m)$.
- Gewünscht: $\mathcal{O}(n + m)$

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- Gewünscht: $\mathcal{O}(n + m)$
- Aho-Corasick-Algorithmus
- Datenstrukturaufbau:
  - NFA, der die NFAs der Einzelmuster verschmilzt
  - DFA daraus
  - Simulation des DFA mit lps-ähnlicher Funktion: Vom aktuellen "tiefsten" aktiven Zustand, finde "nächsthöheren" aktiven Zustand im NFA

Trie

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Definition (Trie)

Der Trie (von *retrieval*) zu einer endlichen Menge von Wörtern $S \subset \Sigma^+$ ist ein kantenbeschrifteter Baum über der Knotenmenge Prefixes(S) mit folgender Eigenschaft:
Der Knoten s ist genau dann ein Kind von Knoten t,
wenn $s = ta$ für ein $a \in \Sigma$;
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Der Aho-Corasick-Algorithmus arbeitet auf dem Trie zur Mustermenge P.

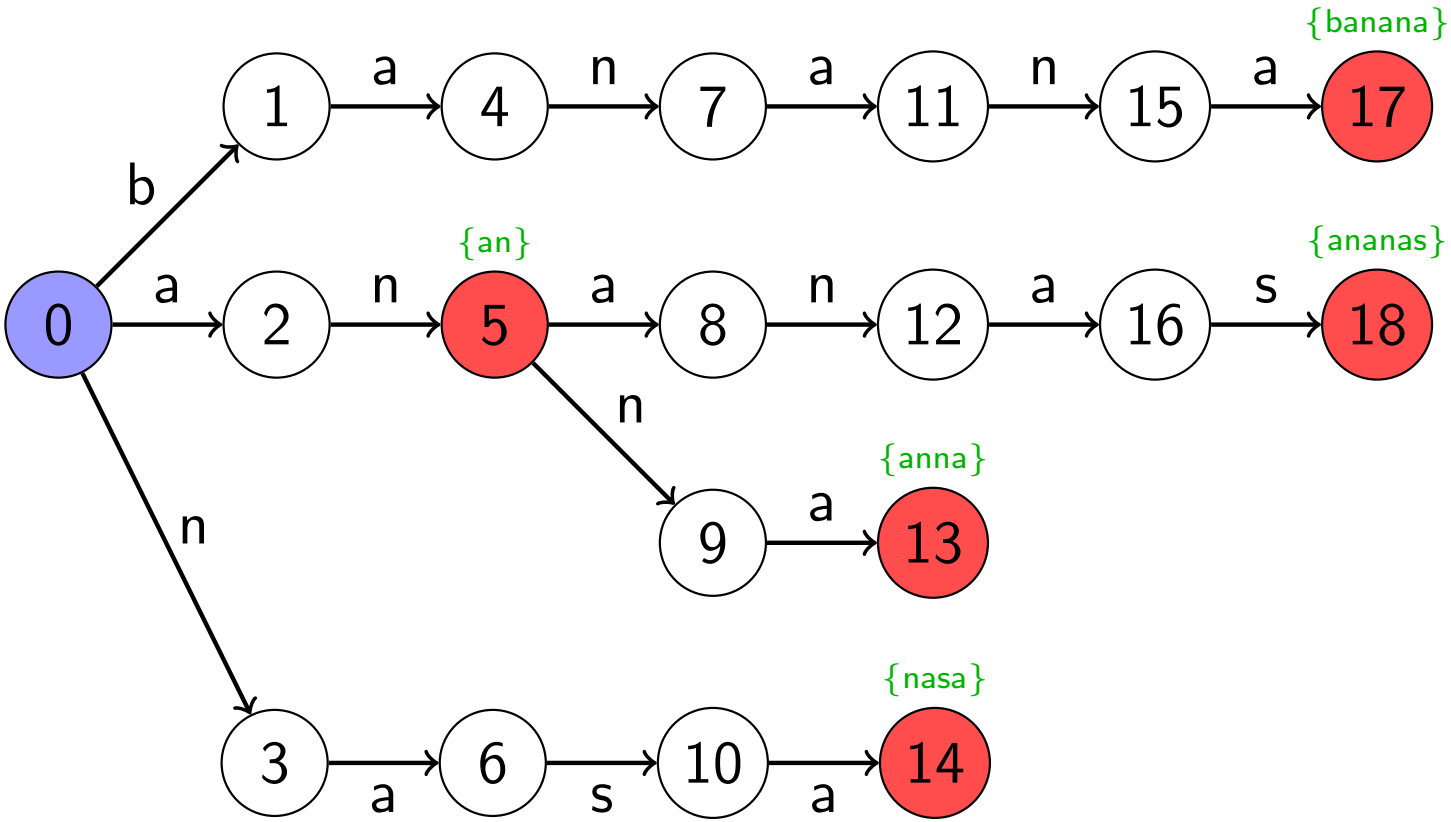
Der Aho-Corasick-Algorithmus

Der AC-Algorithmus verwendet die Idee der lps-Funktion des KMP-Algorithmus auf dem Trie von P. Sei

$$lps(q) := \underset{p \in \text{Prefixes}(P)}{\arg\max} \left\{ |p| \;\middle|\; |p| < |q|,\ p \text{ Suffix von } q \right\}.$$

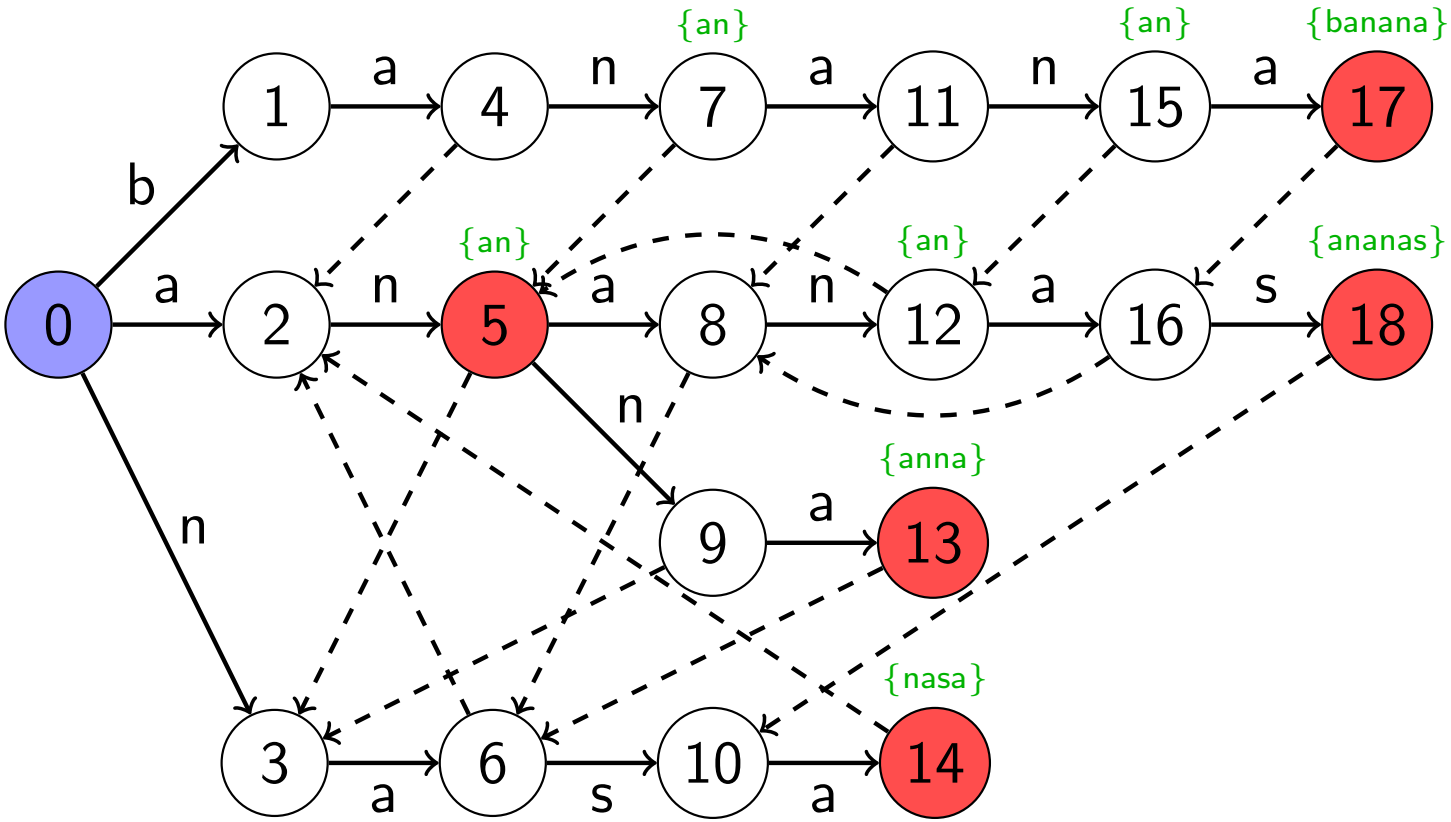
- Hierbei sind q und $lps(q)$ keine Zahlen, sondern Knoten im Trie, die jeweils auf einen String abbilden.
- Die Funktion $lps(q)$ verweist auf den Knoten, der zum längsten Präfix p eines Musters in P gehört, welches gleichzeitig ein echtes Suffix von q ist.

Der Aho-Corasick-Algorithmus



Trie über Mustermenge $P = \{\text{an, ananas, anna, banana, nasa}\}$.
Startzustand: blau; Wörter aus P: rot/grün

Der Aho-Corasick-Algorithmus



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Gestrichelte Pfeile: *lps*-Funktion.

Der Aho-Corasick-Algorithmus

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Erzeugen der *lps*-Funktion:

1. Traversiere den Trie mittels Breitensuche. Beginne beim Startknoten ϵ. $lps[\epsilon]$ ist nicht definiert.

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3. Für alle restlichen Knoten:
   - In Knoten xa, setze $v := x$.
   - Prüfe, ob Knoten $lps[v]$ eine ausgehende Kante a hat.
   - Wenn ja, setze $lps[xa] := lps[v]a$.
   - Sonst gehe solange über zu $v := lps[v]$, bis entweder $lps[v]$ nicht mehr existiert oder es eine ausgehende Kante a von v gibt. Im letzteren Fall setze wieder $lps[xa] := lps[v]a$.

Der Aho-Corasick-Algorithmus

Ausgabe der gefundenen Muster:

- Es findet eine Ausgabe statt, wenn der aktuelle Knoten
  - einem akzeptierenden Zustand entspricht.
  - über (mehrfache) *lps*-Transitionen einen akzeptierenden Zustand erreicht.

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  - einem akzeptierenden Zustand entspricht.
  - über (mehrfache) *lps*-Transitionen einen akzeptierenden Zustand erreicht.
- Die Indizes der auszugebenden Muster können
  - im Knoten als Index abgespeichert werden. Bei der Ausgabe wird den *lps*-Transitionen gefolgt, um alle Wörter auszugeben.
  - direkt im Knoten als Liste durch Konkatenation mit ihren *lps*-Vorgängern abgespeichert werden.

Der Aho-Corasick-Algorithmus

Implementierung:
Es wird eine Klasse `ACNode` mit folgenden Attributen angelegt:

- Ein Dictionary *targets* : $c \rightarrow q$ mit $c \in \Sigma, q \in \text{Prefixes}(P)$ zum speichern der Kinderknoten.
- Eine Referenz *lps* auf den *lps*-Vorgängerknoten.
- Eine Liste *out* mit den Indizes der auszugebenden Muster.

```
1 class ACNode():
2     def __init__(self):
3         self.targets = dict()
4         self.lps = None
5         self.out = []
```

Der Aho-Corasick-Algorithmus

Implementierung:
Die *delta*-Funktion ist ähnlich aufgebaut, wie die *delta*-Funktion des KMP, nur dass die Zustände hierbei durch Knoten abgebildet werden.

```
1 def delta(q, c):
2     while (q.lps is not None) and (c not in q.targets):
3         q = q.lps
4     if c in q.targets:
5         q = q.targets[c]
6     return q
```

Der Aho-Corasick-Algorithmus

Implementierung:
Das Erstellen des Aho-Corasick-Automates ist aufgeteilt in zwei Phasen:

1. Erstellen des Tries.
2. Hinzufügen der *lps*-Kanten.

```
1 def build_AC(P):
2     root = build_trie(P)
3     build_lps(root)
4     return root
```

Der Aho-Corasick-Algorithmus

Implementierung:

```
1  def build_trie(P):
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3      for (i, p) in enumerate(P):
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9          node.out.append(i)
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Der Aho-Corasick-Algorithmus

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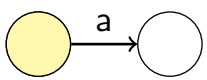

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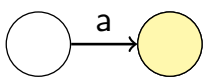

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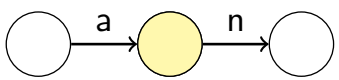

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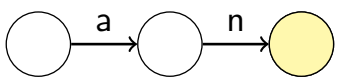

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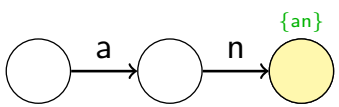

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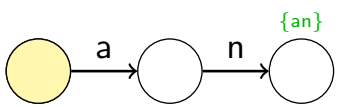

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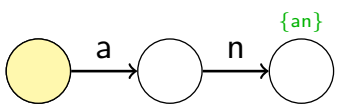

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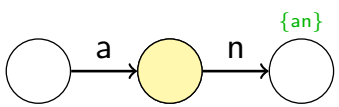

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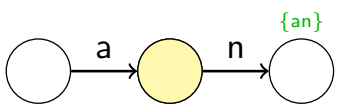

Der Aho-Corasick-Algorithmus

UA RUHR

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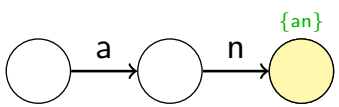

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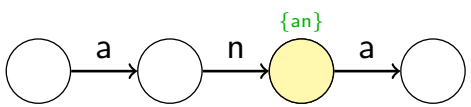

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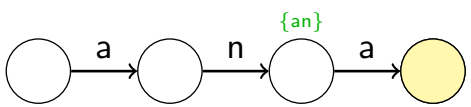

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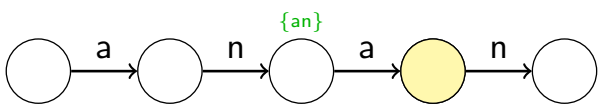

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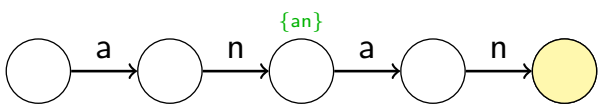

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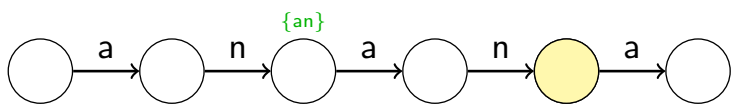

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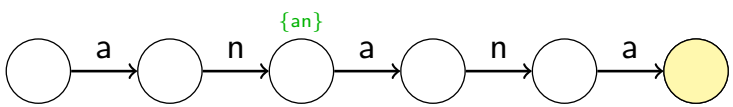

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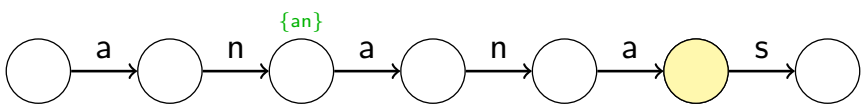

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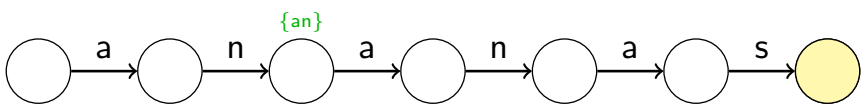

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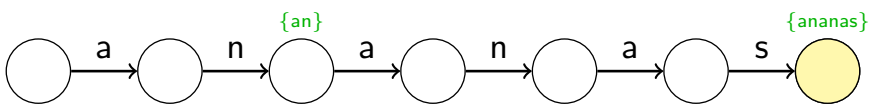

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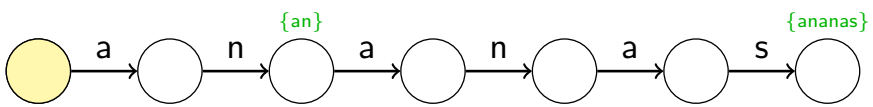

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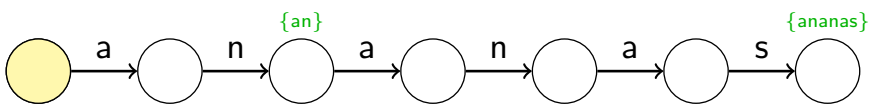

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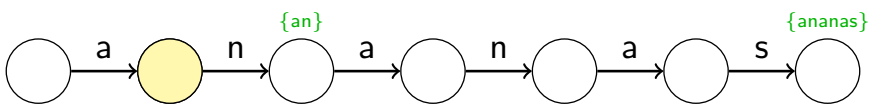

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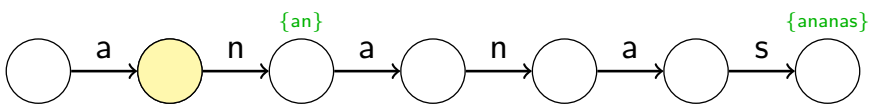

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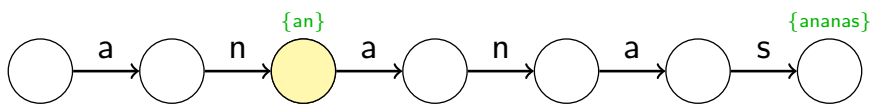

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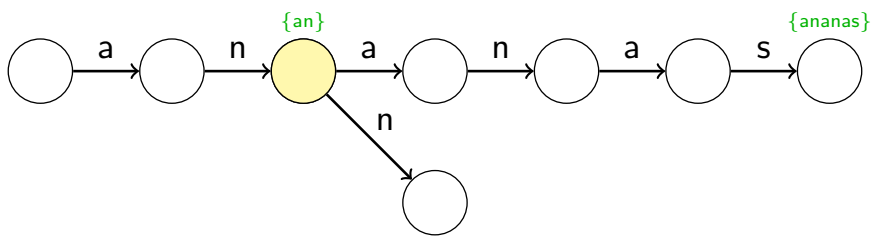

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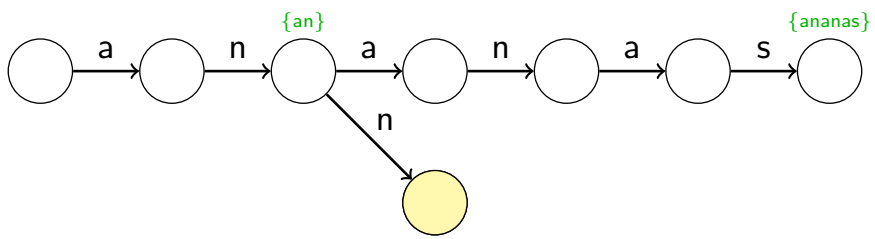

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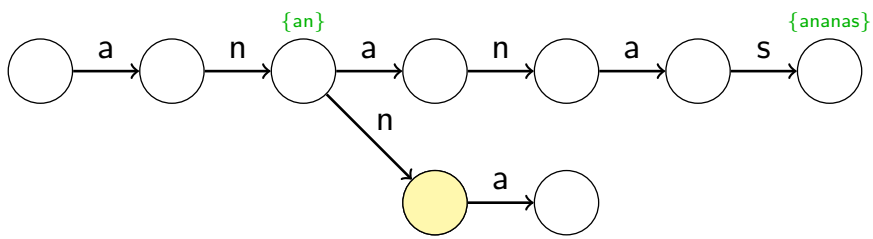

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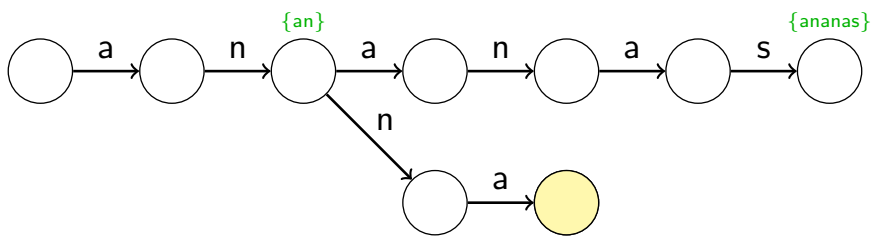

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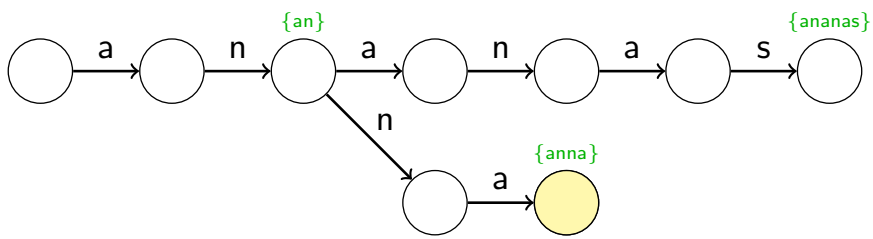

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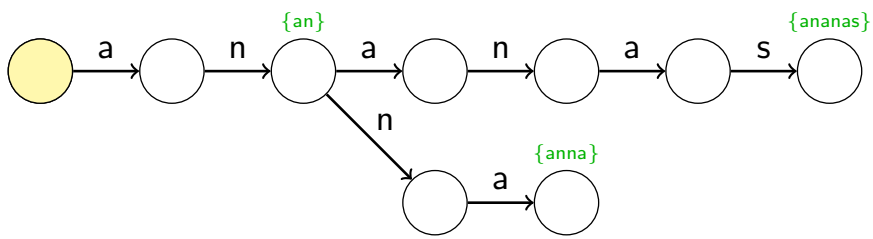

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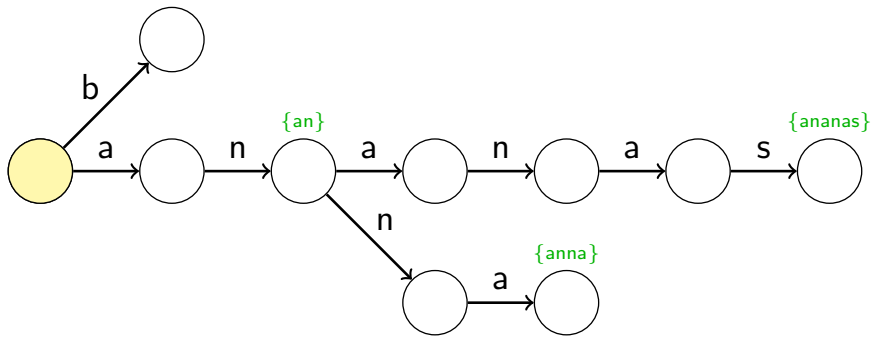

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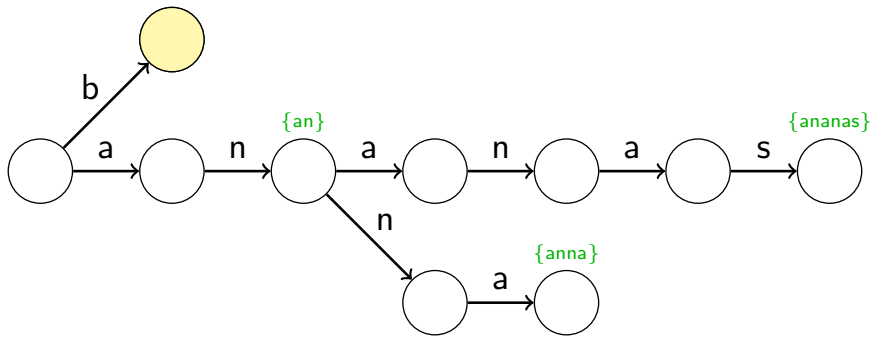

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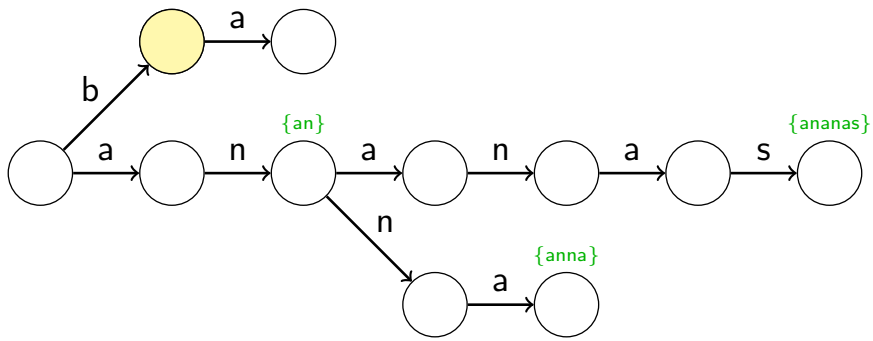

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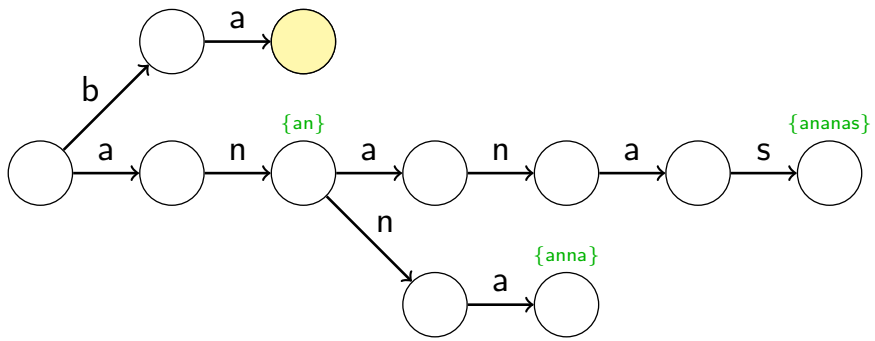

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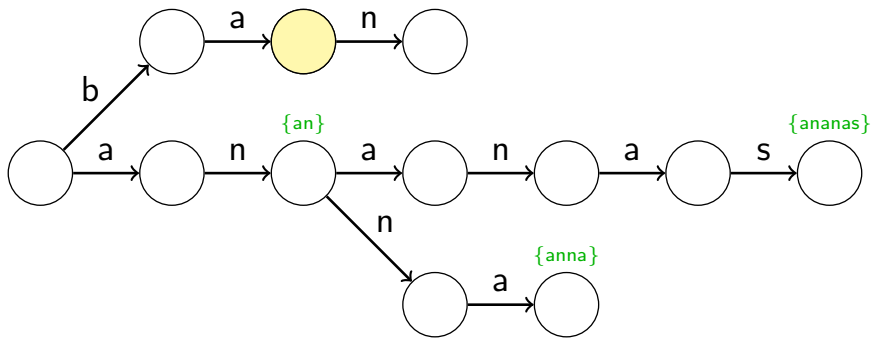

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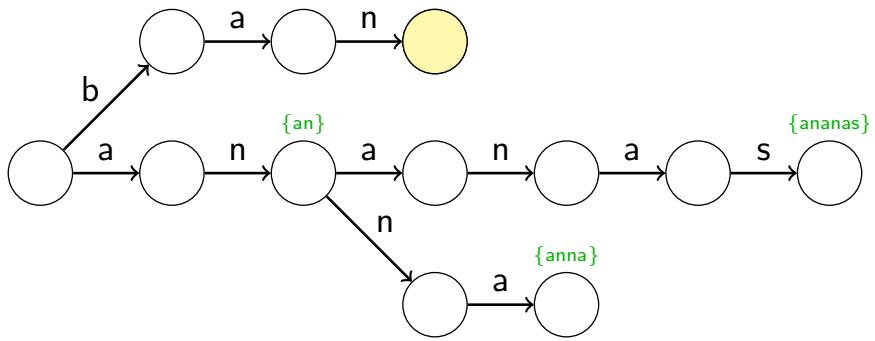

Der Aho-Corasick-Algorithmus

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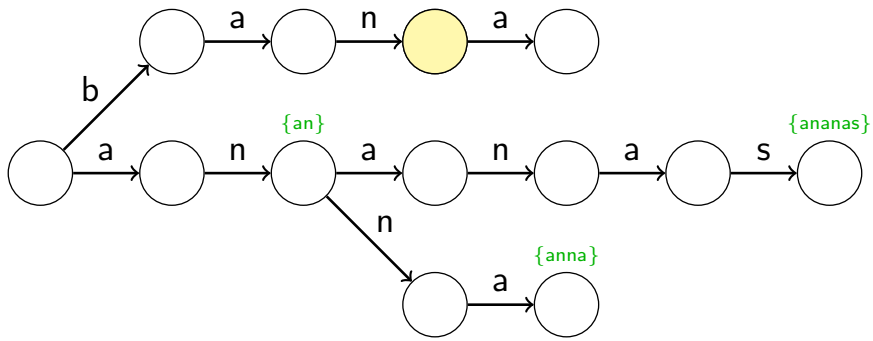

Der Aho-Corasick-Algorithmus

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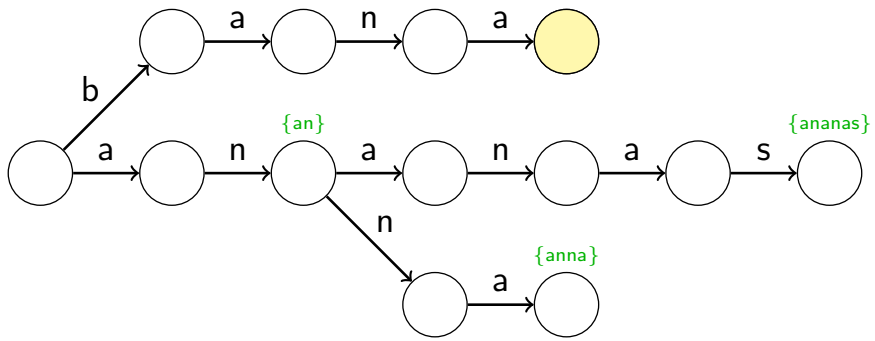

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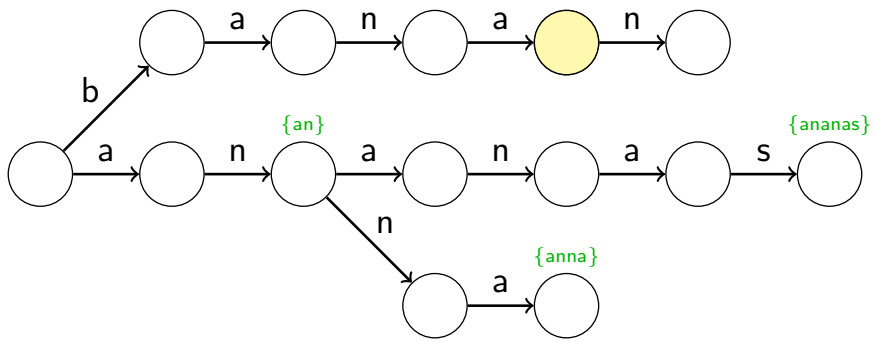

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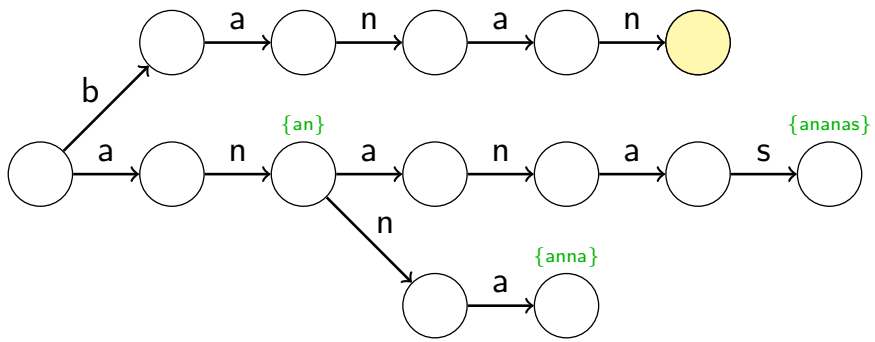

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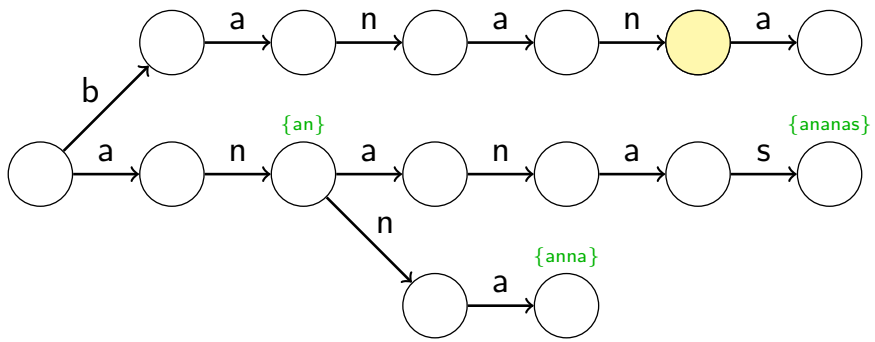

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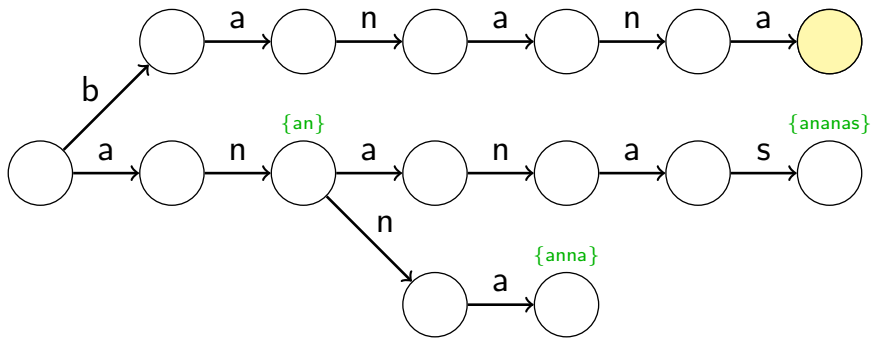

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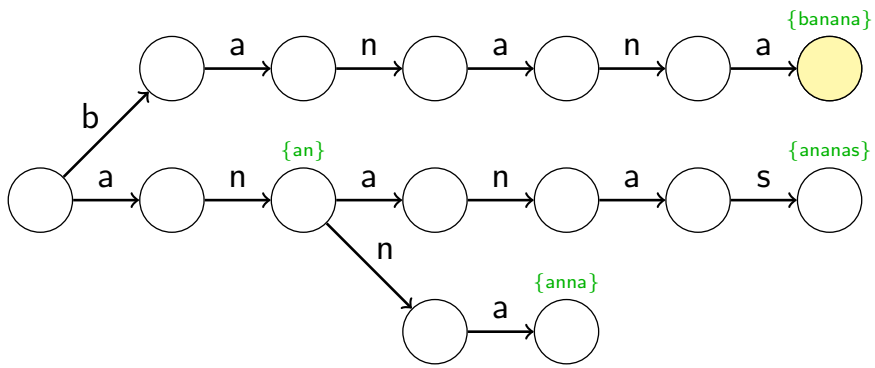

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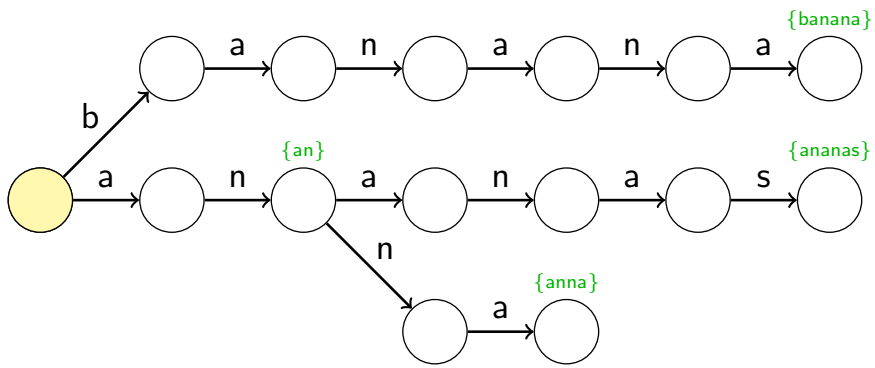

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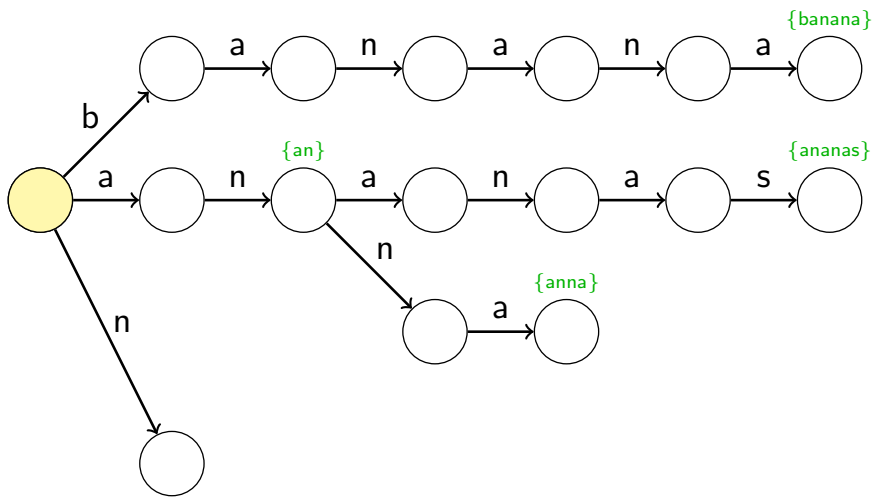

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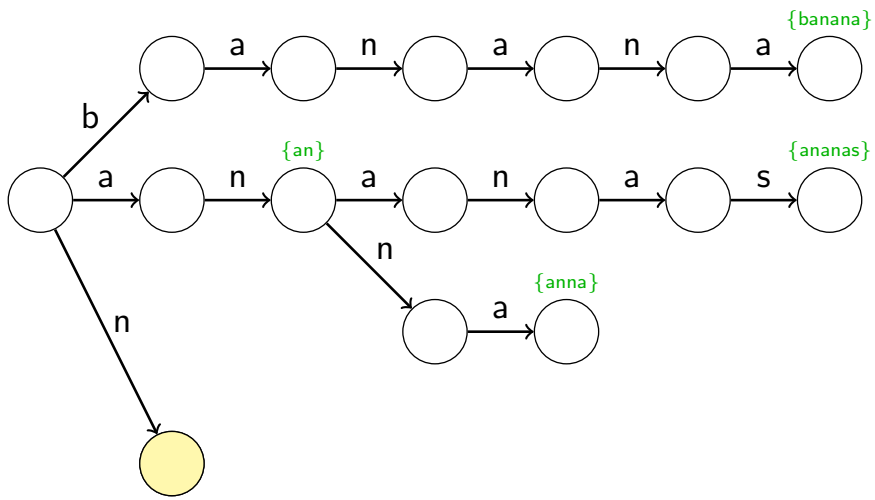

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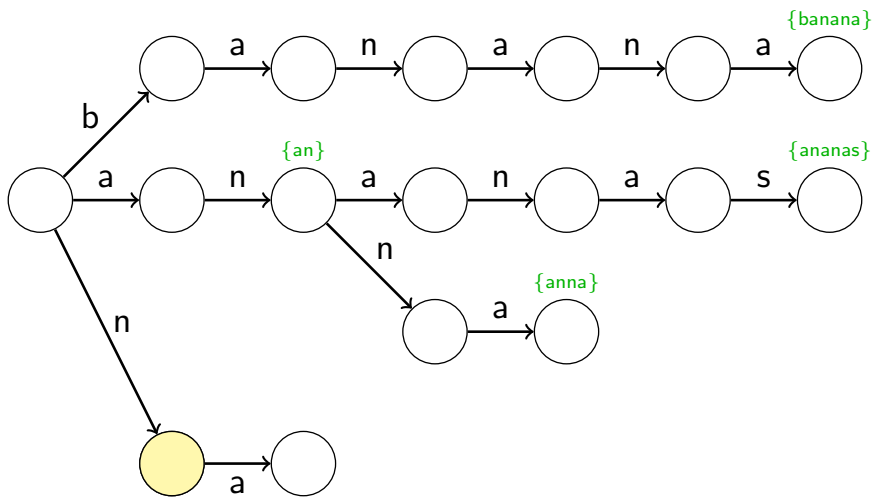

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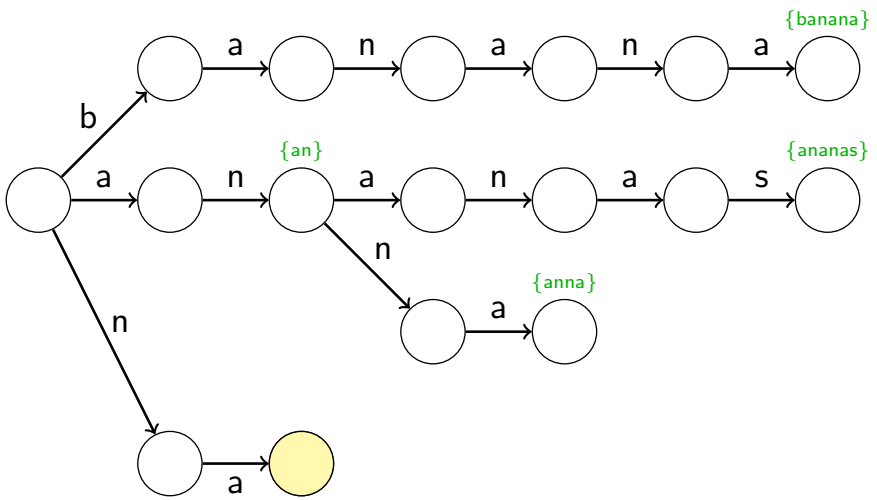

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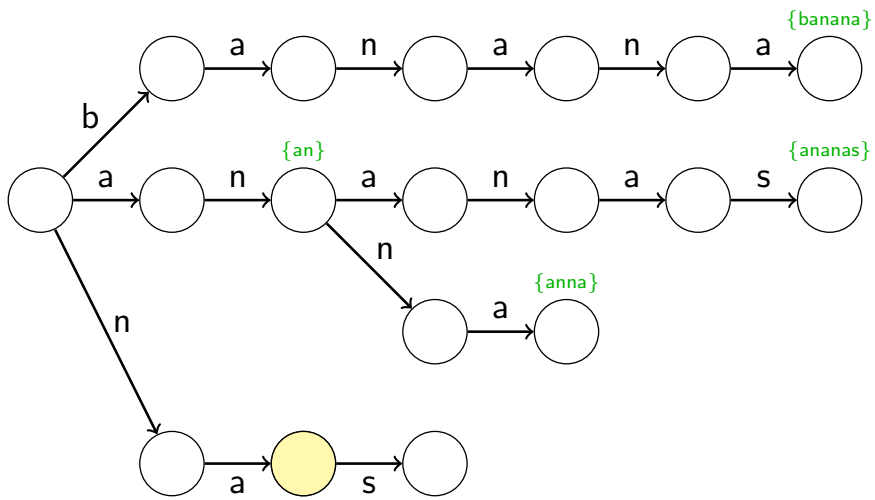

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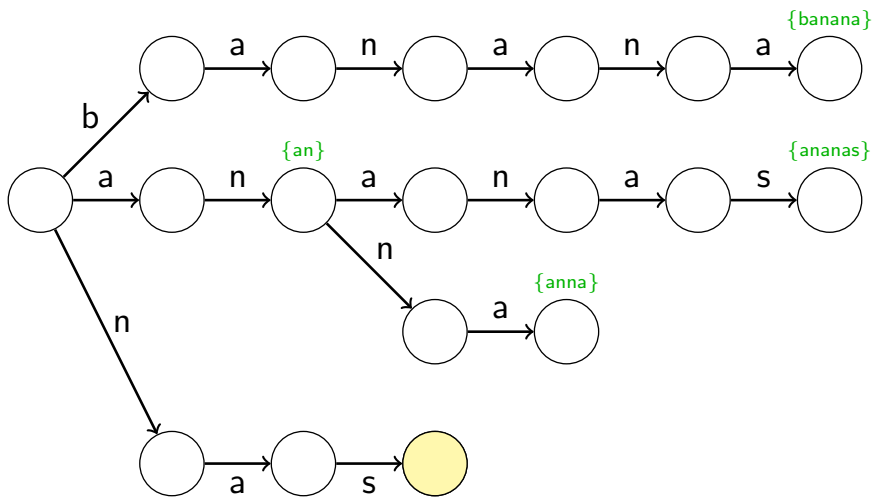

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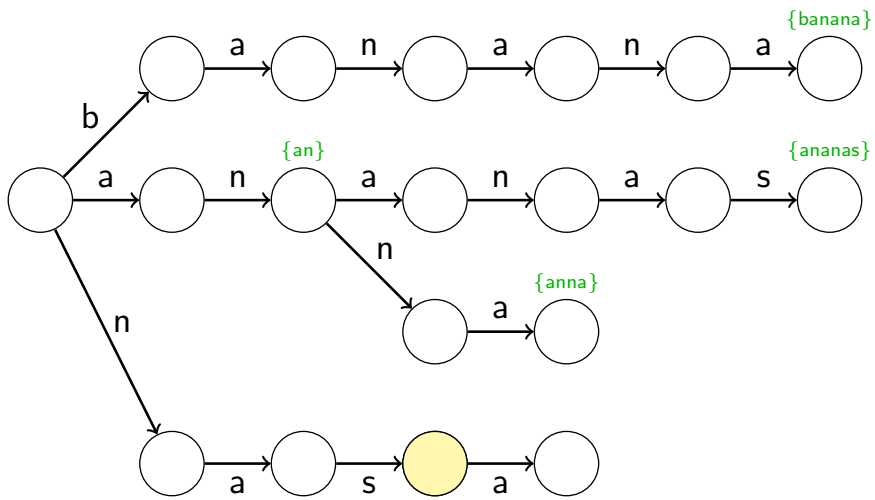

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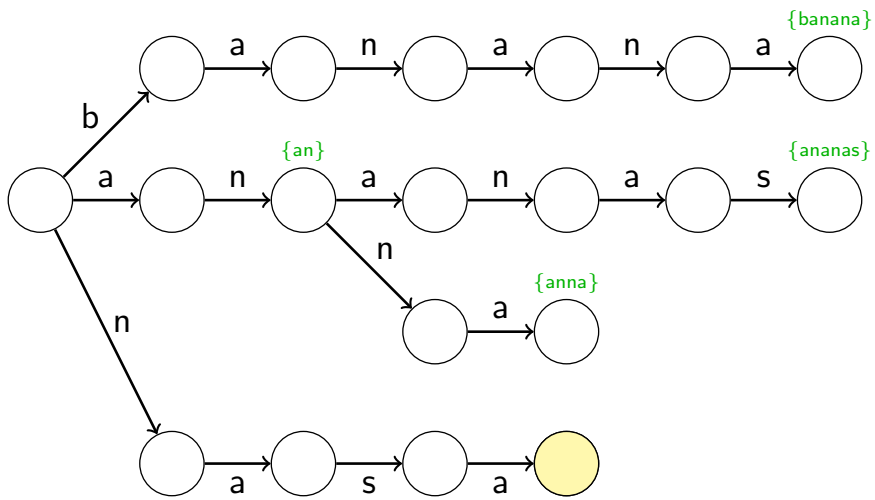

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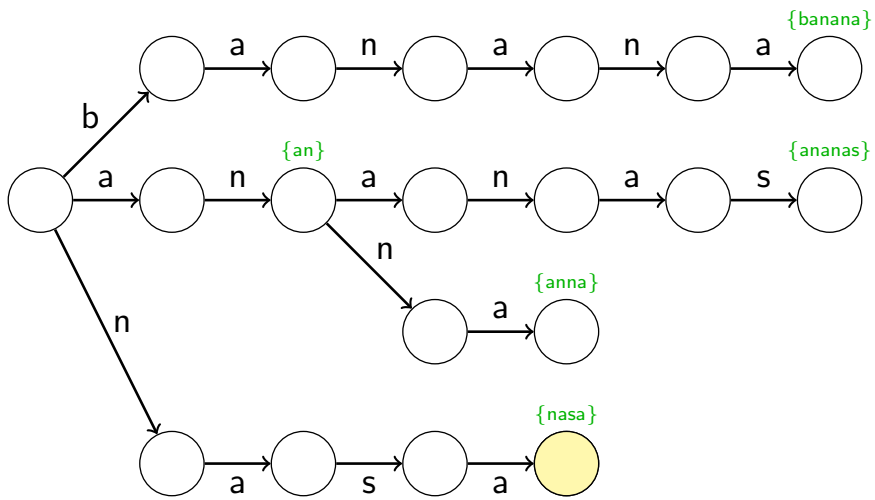

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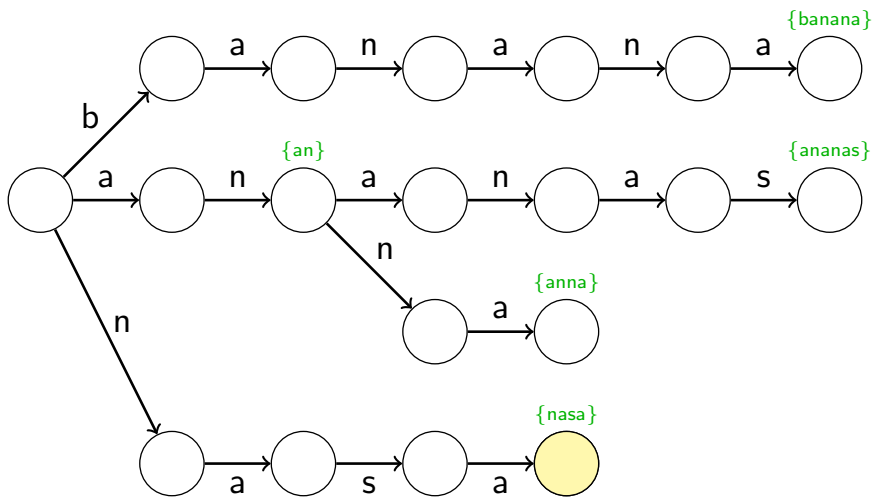

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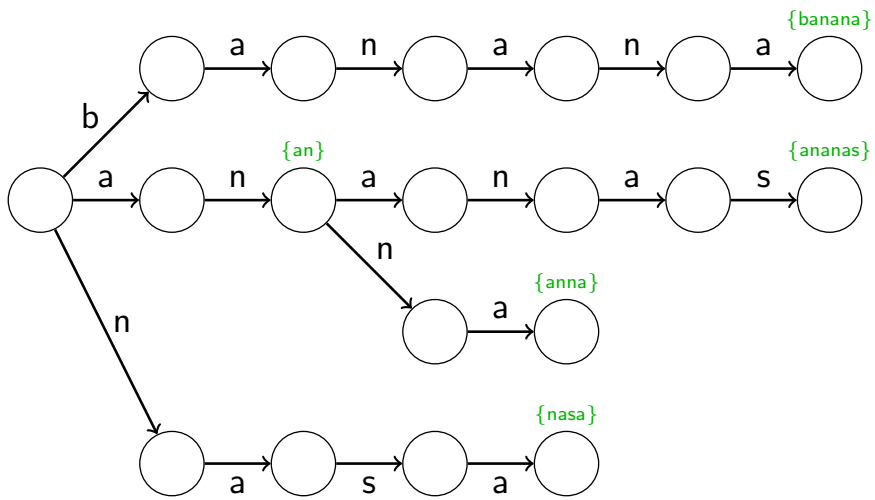


Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

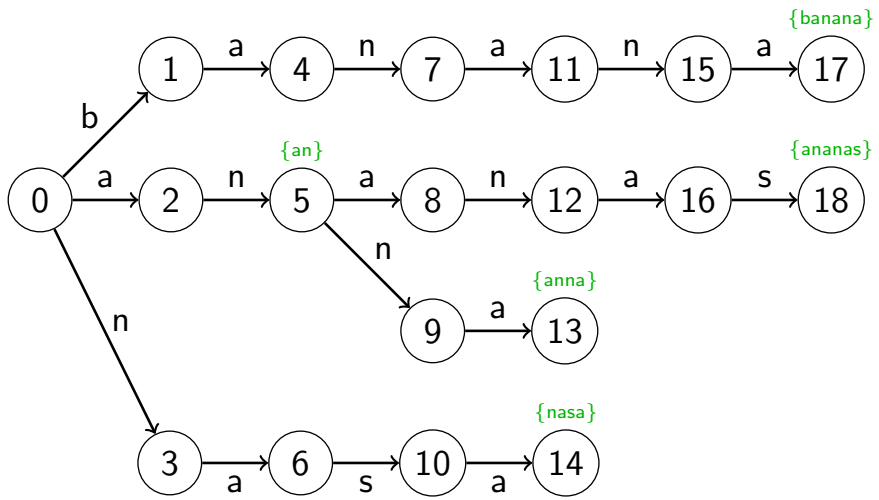
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q =$ []

node =

letter =

parent =



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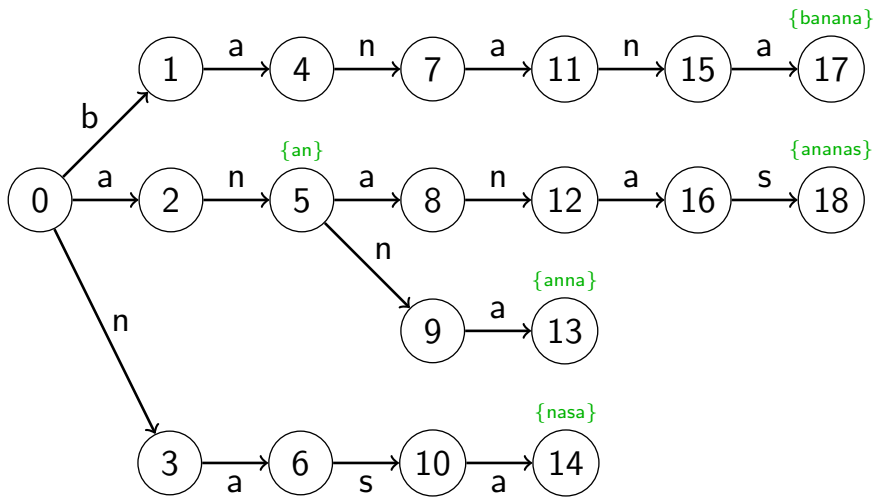
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q =$ $[(0, \emptyset, \emptyset)]$

node =

letter =

parent =



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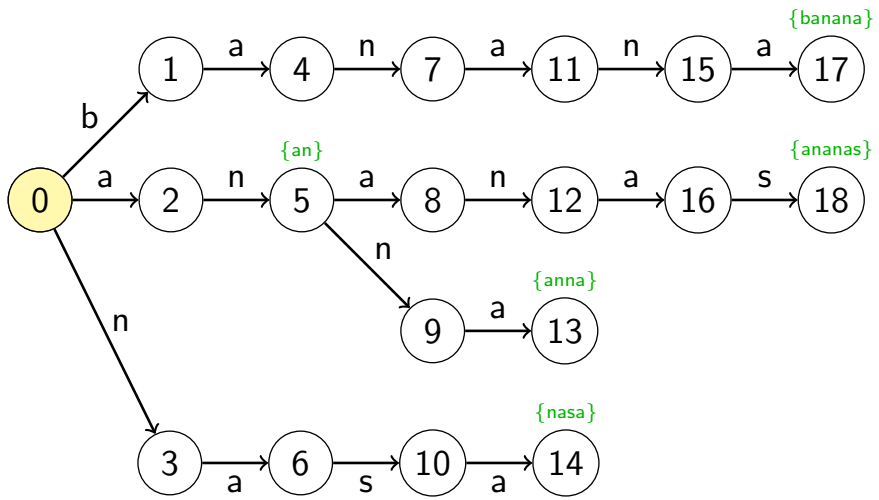
```

$Q =$ []

$node =$ 0

$letter =$ $\emptyset$

$parent =$ $\emptyset$



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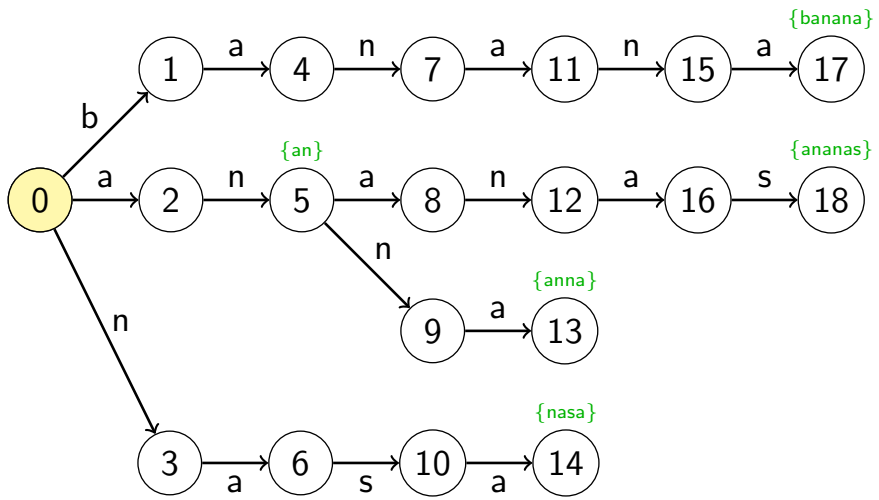
```

$Q = [(1, b, 0), (2, a, 0), (3, n, 0)]$

$node =$ 0

$letter = \emptyset$

$parent = \emptyset$



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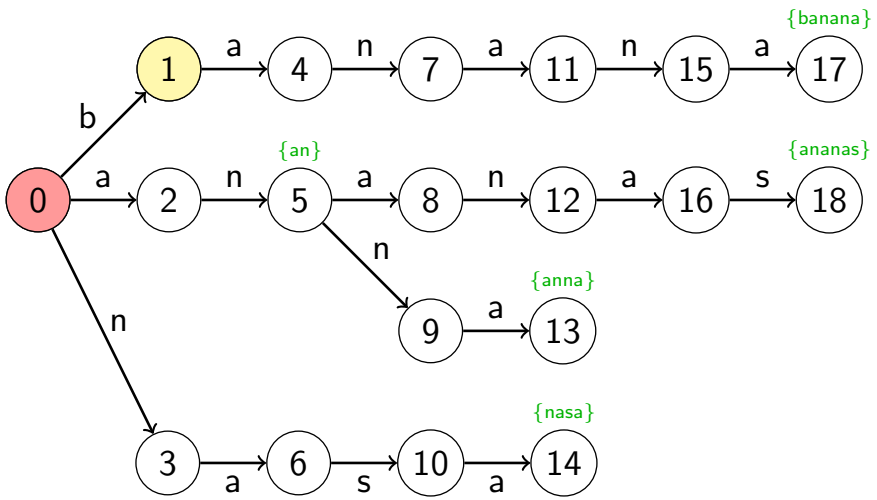
```

$Q = [(2, a, 0), (3, n, 0)]$

$node =$ 1

$letter =$ b

$parent =$ 0



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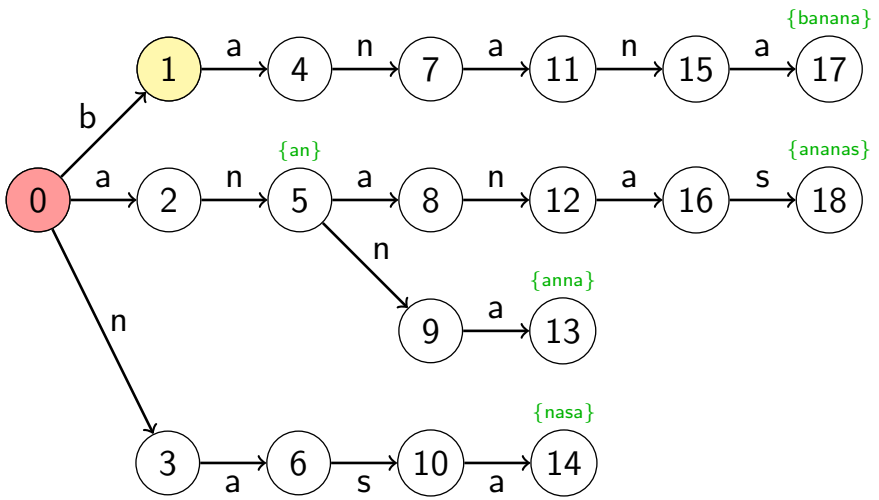
```

$Q = [(2, a, 0), (3, n, 0), (4, a, 1)]$

$node =$ 1

$letter =$ b

$parent =$ 0



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$Q = [(2, a, 0), (3, n, 0), (4, a, 1)]$

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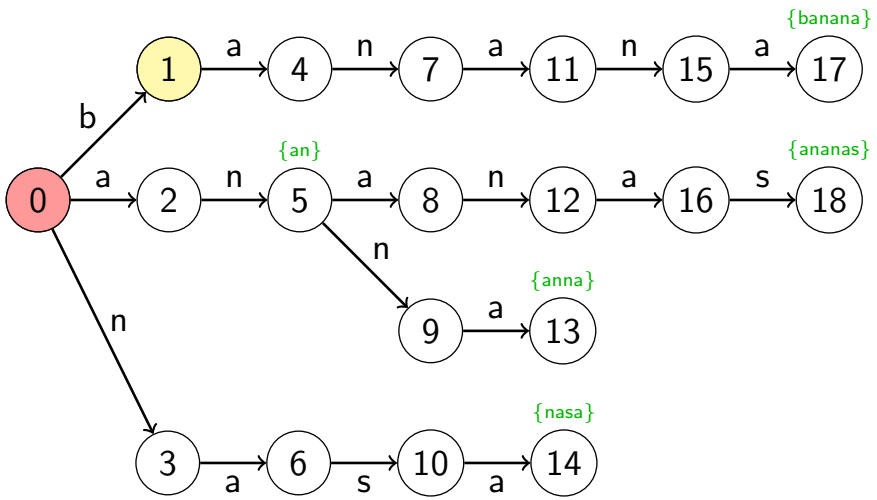


Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

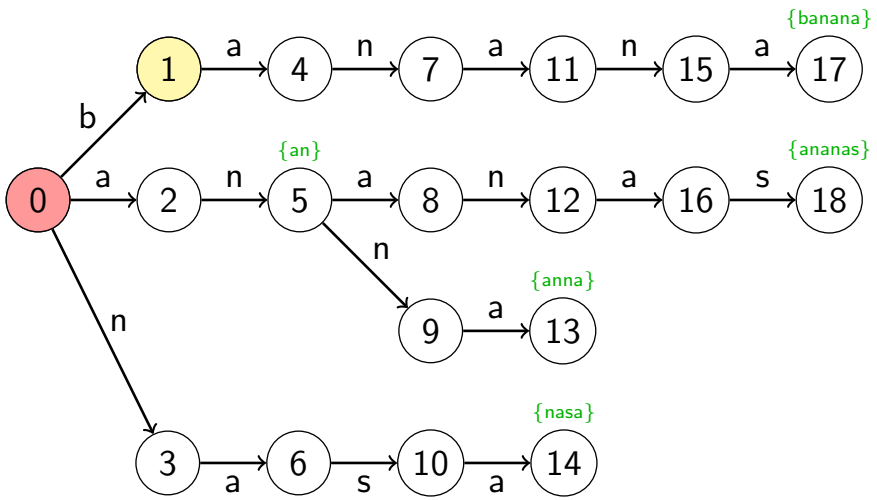
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(2, a, 0), (3, n, 0), (4, a, 1)]$

$node =$ 1

$letter =$ b

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

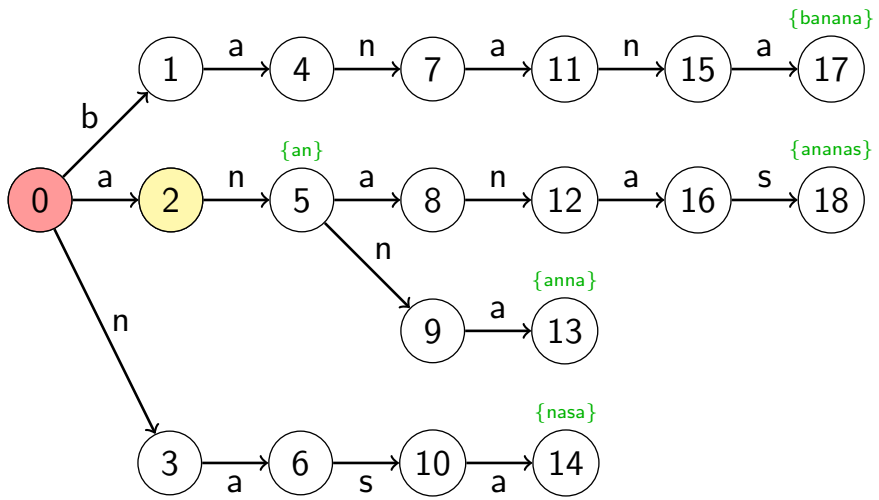
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(3, n, 0), (4, a, 1)]$

$node =$ 2

$letter =$ a

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

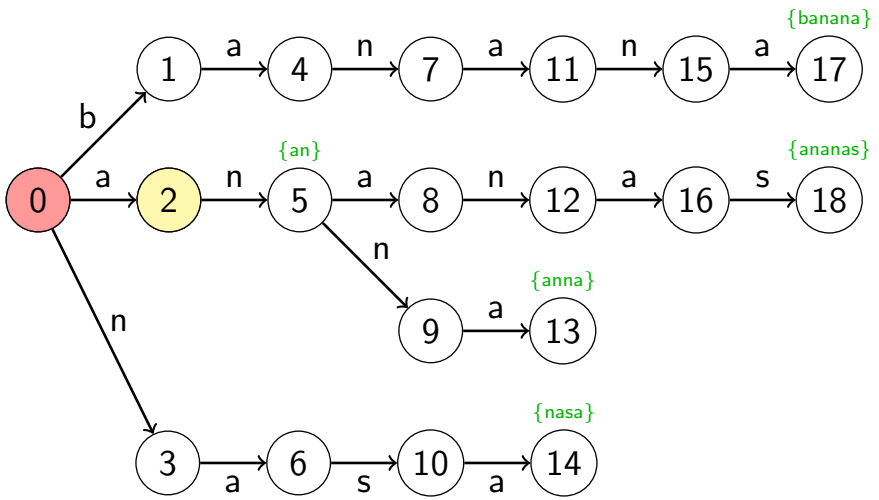
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(3, n, 0), (4, a, 1), (5, n, 2)]$

$node =$ 2

$letter =$ a

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

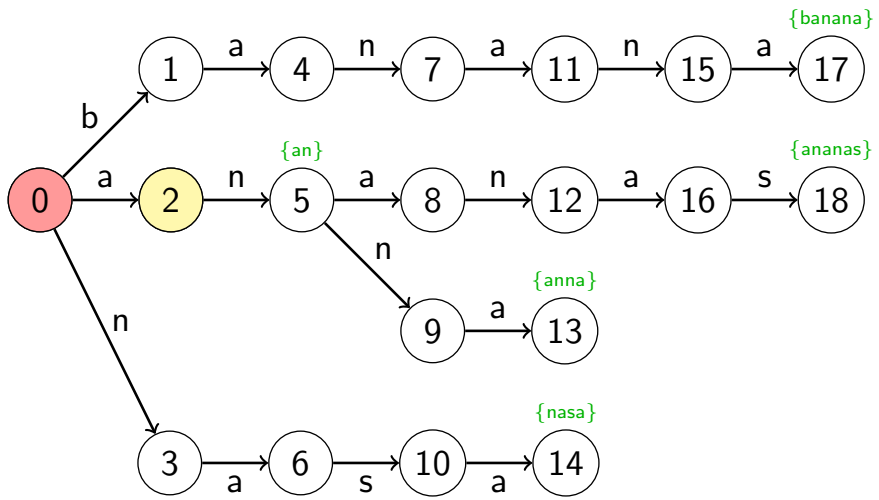
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(3, n, 0), (4, a, 1), (5, n, 2)]$

$node =$ 2

$letter =$ a

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

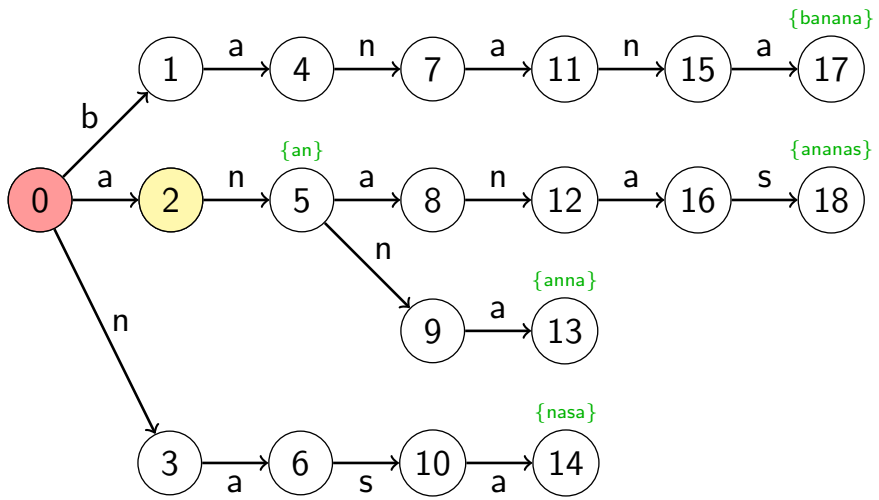
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(3, n, 0), (4, a, 1), (5, n, 2)]$

$node =$ 2

$letter =$ a

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

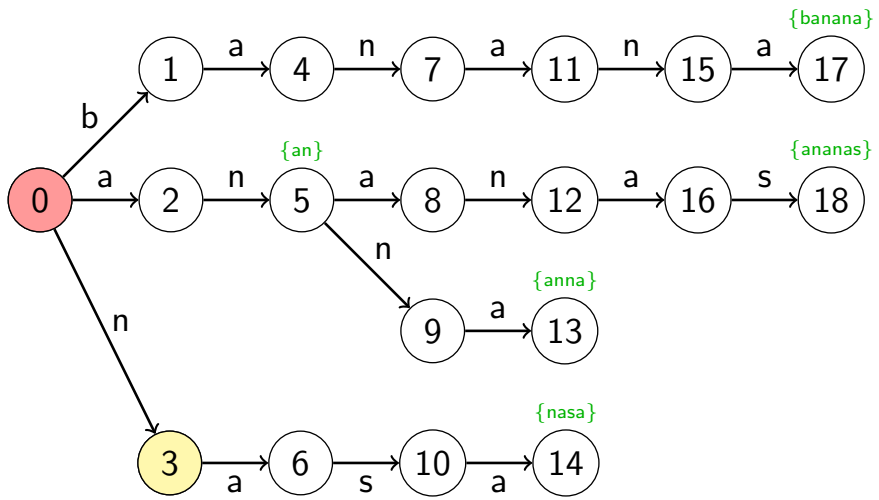
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(4, a, 1), (5, n, 2)]$

$node =$ 3

$letter =$ n

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

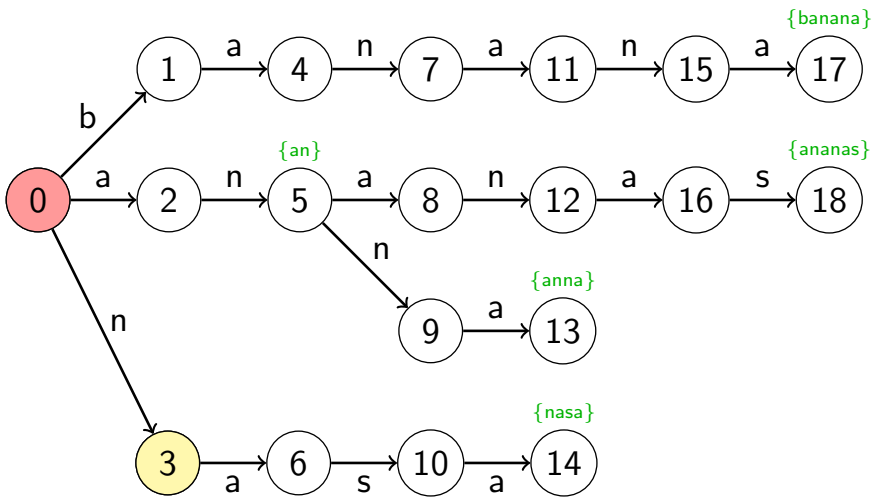
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(4, a, 1), (5, n, 2), (6, a, 3)]$

$node =$ 3

$letter =$ n

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

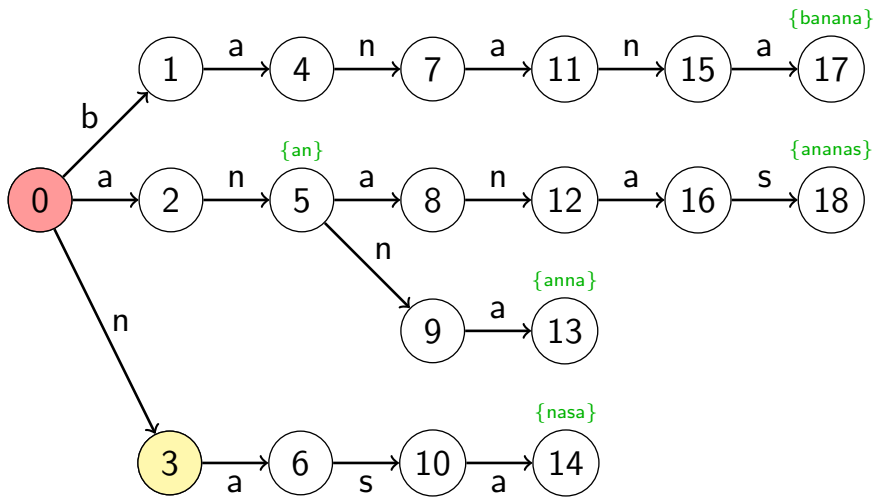
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(4, a, 1), (5, n, 2), (6, a, 3)]$

$node =$ 3

$letter =$ n

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

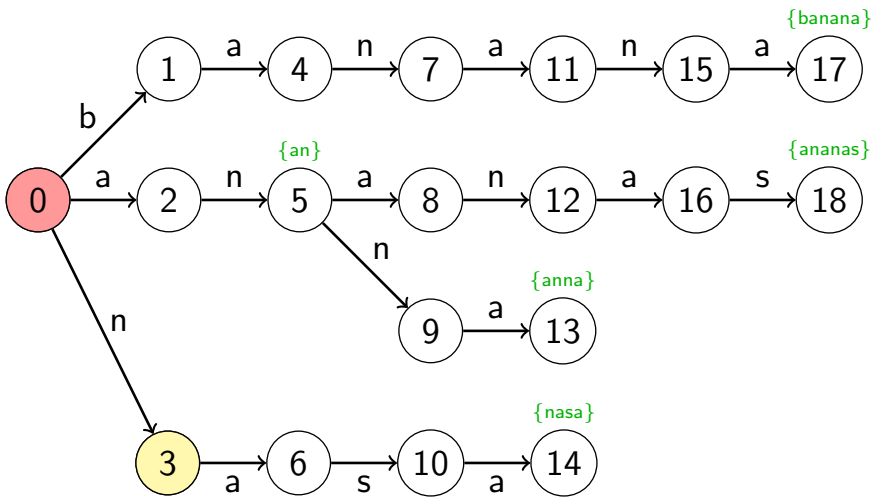
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(4, a, 1), (5, n, 2), (6, a, 3)]$

$node =$ 3

$letter =$ n

$parent =$ 0



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

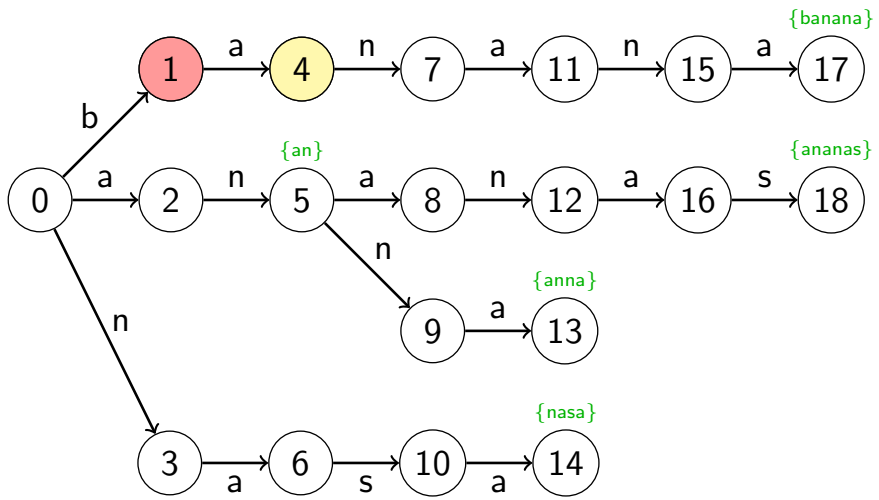
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

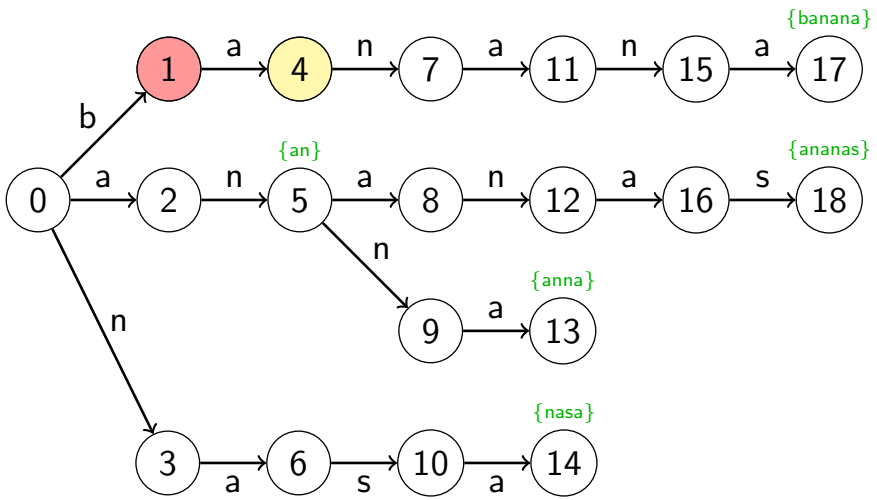
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3), (7, n, 4)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

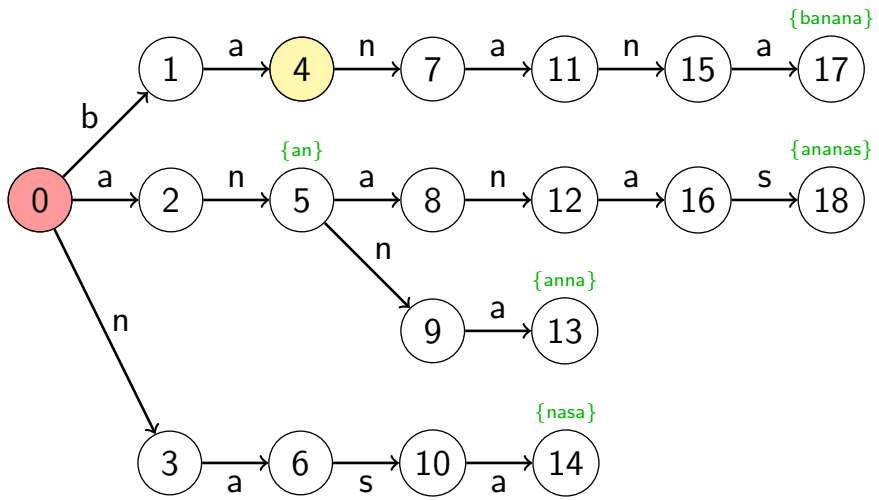
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3), (7, n, 4)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

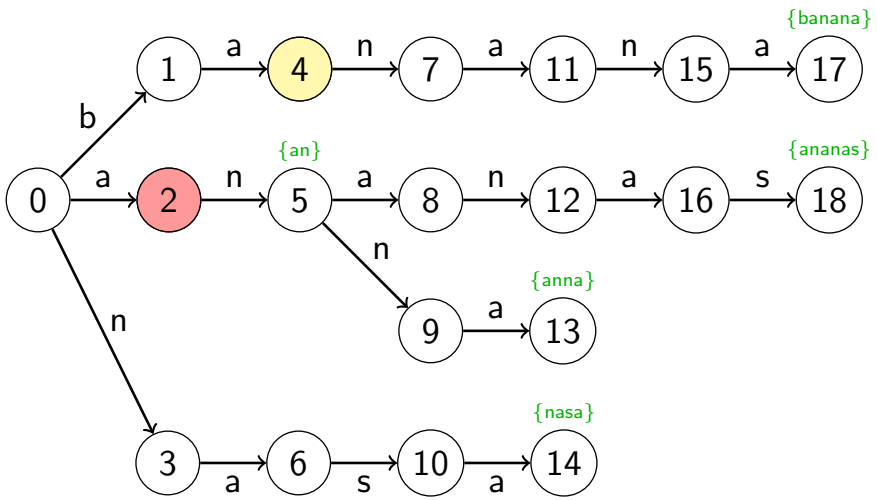
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3), (7, n, 4)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

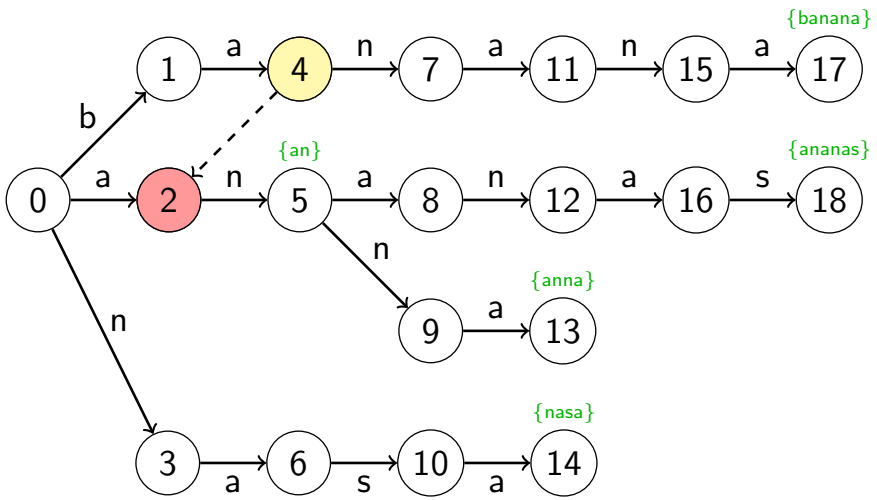
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3), (7, n, 4)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

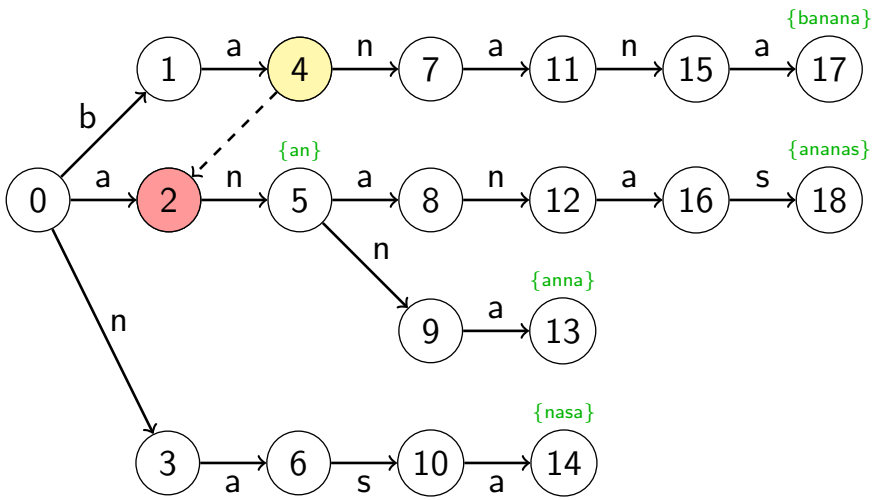
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(5, n, 2), (6, a, 3), (7, n, 4)]$

$node =$ 4

$letter =$ a

$parent =$ 1



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

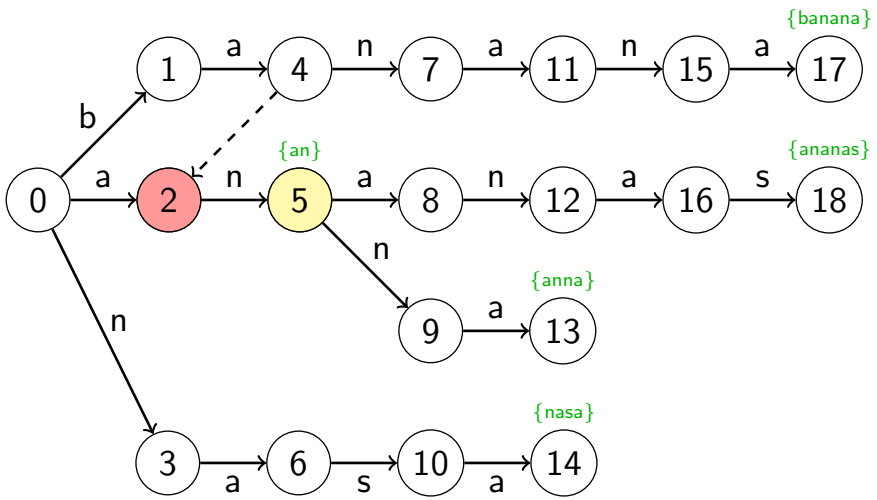
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3), (7, n, 4)]$

$node =$ 5

$letter =$ n

$parent =$ 2



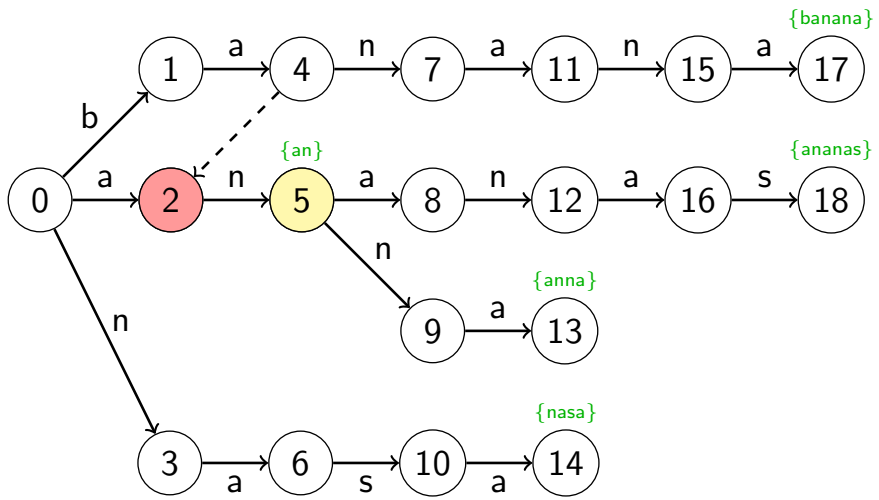
Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3),$
$(7, n, 4),$
$(8, a, 5),$
$(9, n, 5)]$

$node =$ 5
$letter =$ n
$parent =$ 2



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
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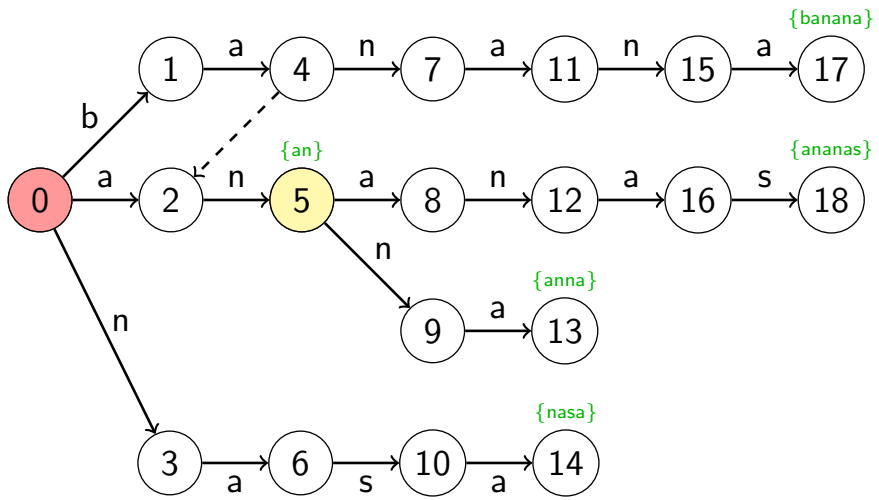
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3), (7, n, 4), (8, a, 5), (9, n, 5)]$

$node = 5$

$letter = \text{n}$

$parent = 2$



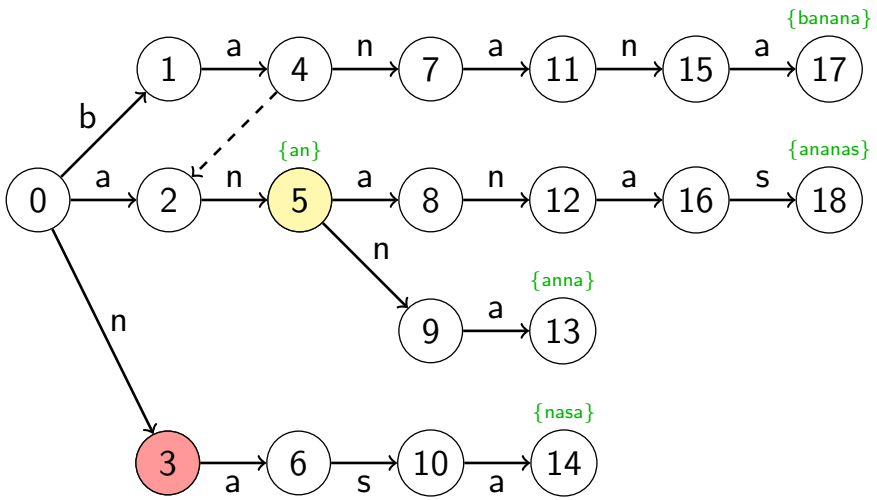
Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3),$
$(7, n, 4),$
$(8, a, 5),$
$(9, n, 5)]$

$node =$ 5
$letter =$ n
$parent =$ 2



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

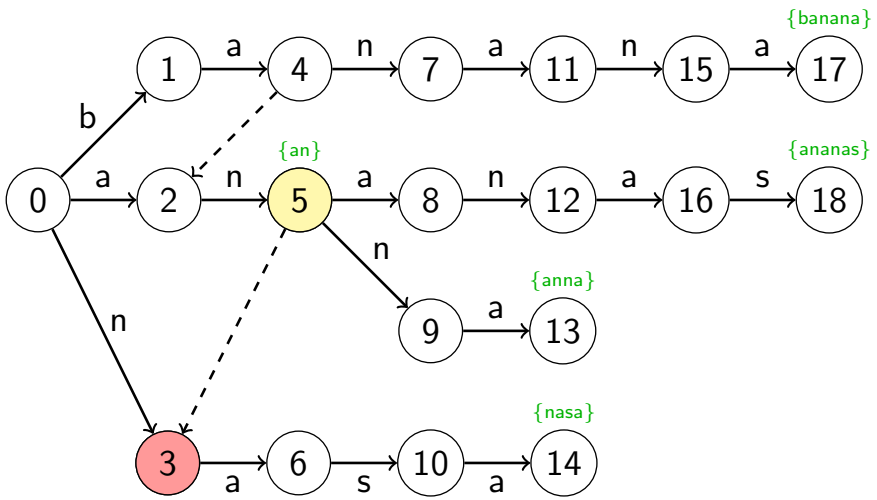
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3),$
$(7, n, 4),$
$(8, a, 5),$
$(9, n, 5)]$

$node =$ 5

$letter =$ n

$parent =$ 2



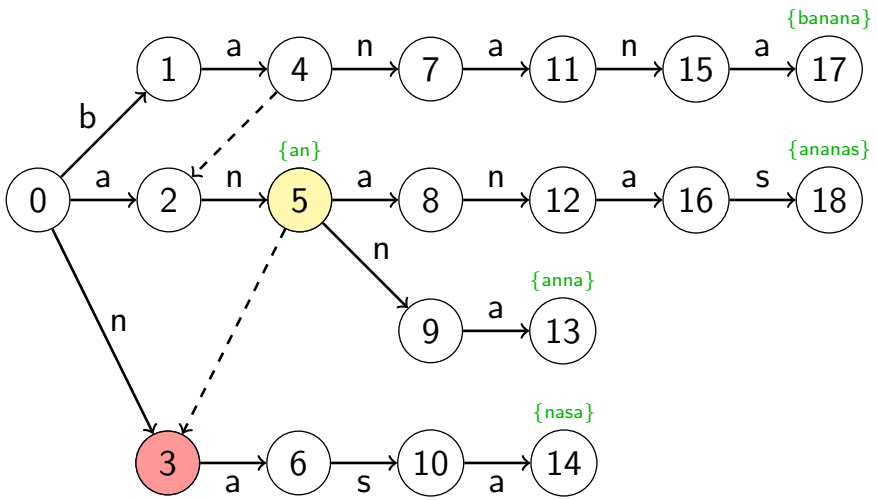
Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(6, a, 3),$
$(7, n, 4),$
$(8, a, 5),$
$(9, n, 5)]$

$node =$ 5
$letter =$ n
$parent =$ 2



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

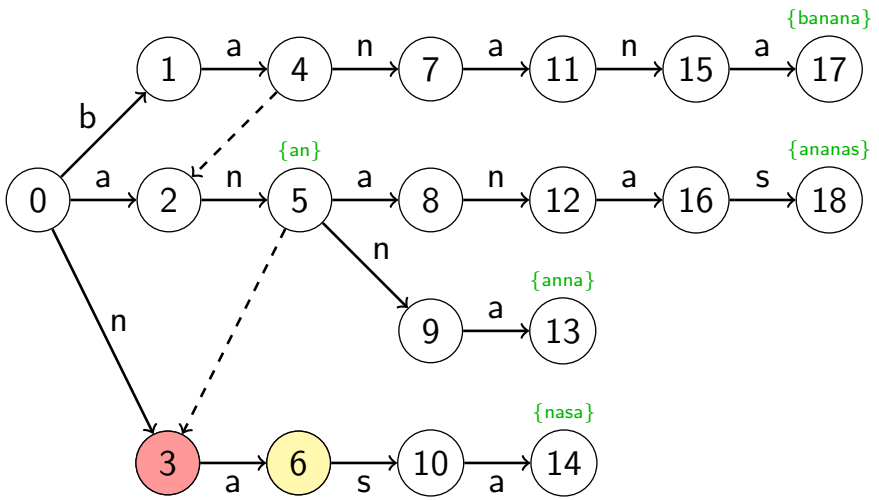
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(7, n, 4), (8, a, 5), (9, n, 5)]$

$node =$ 6

$letter =$ a

$parent =$ 3



Der Aho-Corasick-Algorithmus

Erstellung der *lps*-Kanten:

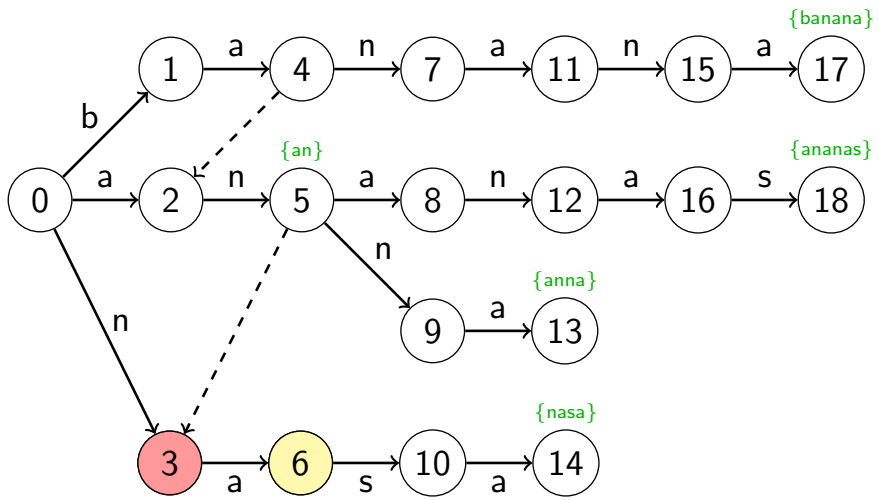
```
1  def build_lps(root):
2      Q = [(root, None, None)]   # (child, letter to child, parent)
3      while Q:
4          (node, letter, parent) = Q.pop(0)
5          Q.extend([(v, k, node) for k, v in node.targets.items()])
6          if parent is None:  continue
7          node.lps = delta(parent.lps, letter)  if parent != root  else root
8          node.out.extend(node.lps.out)
```

$Q = [(7, n, 4), (8, a, 5), (9, n, 5), (10, s, 6)]$

$node = 6$

$letter = a$

$parent = 3$



Der Aho-Corasick-Algorithmus

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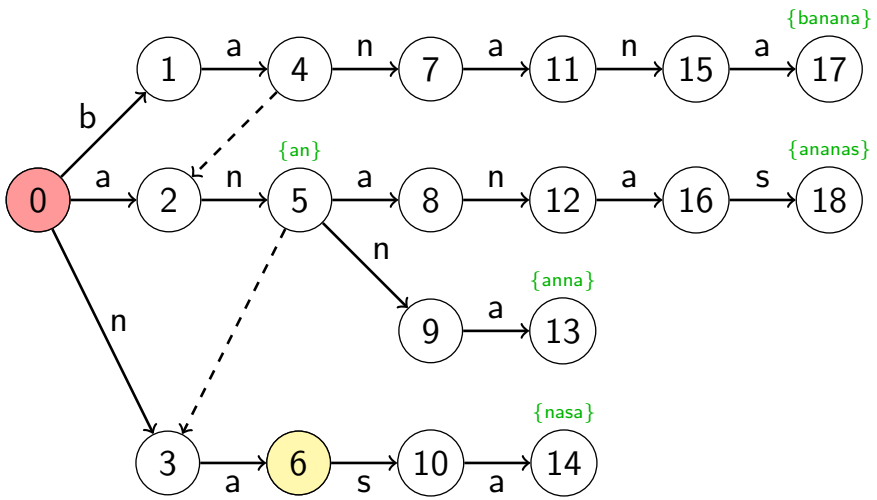

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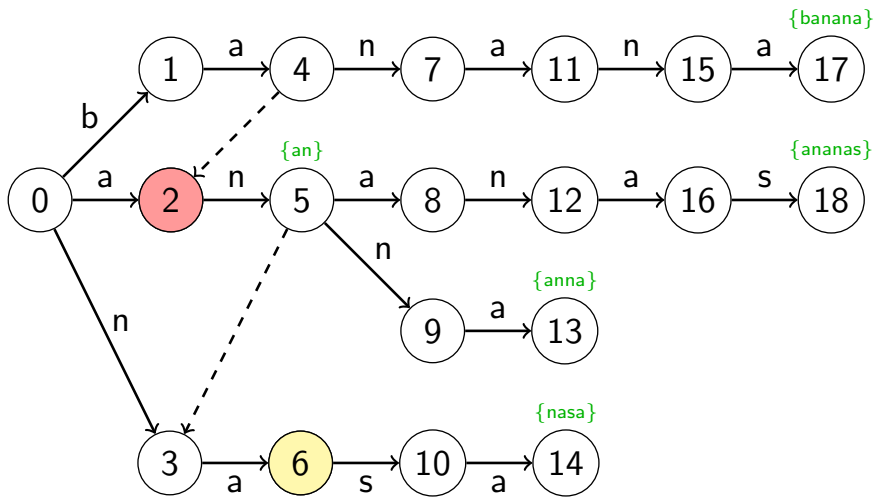

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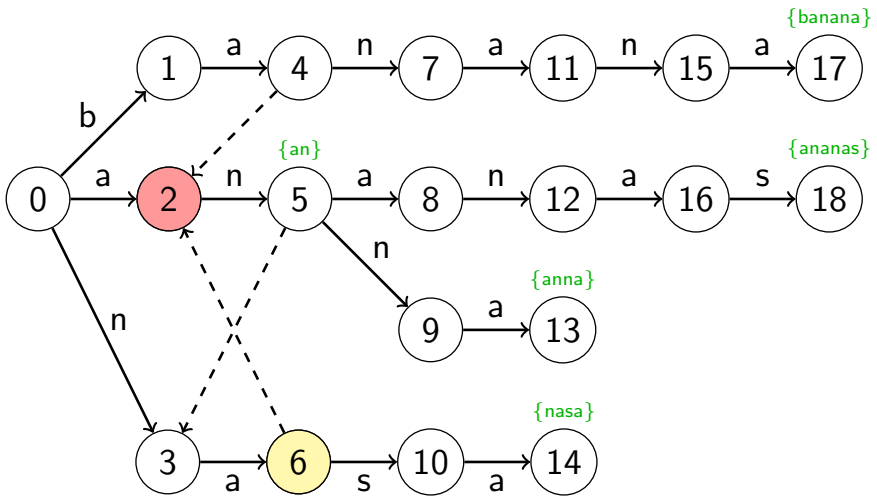

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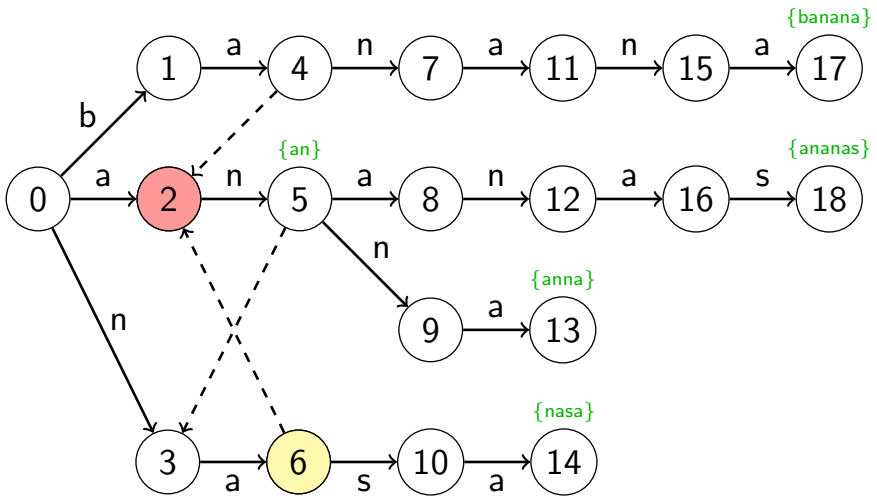

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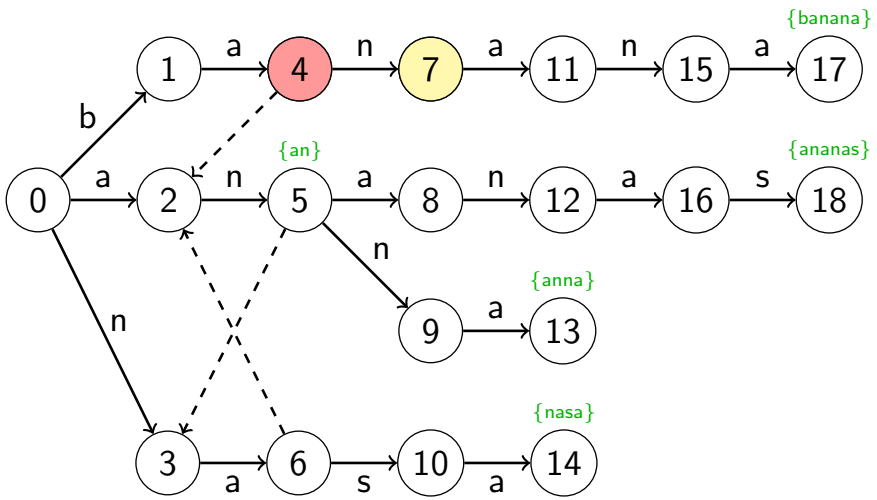

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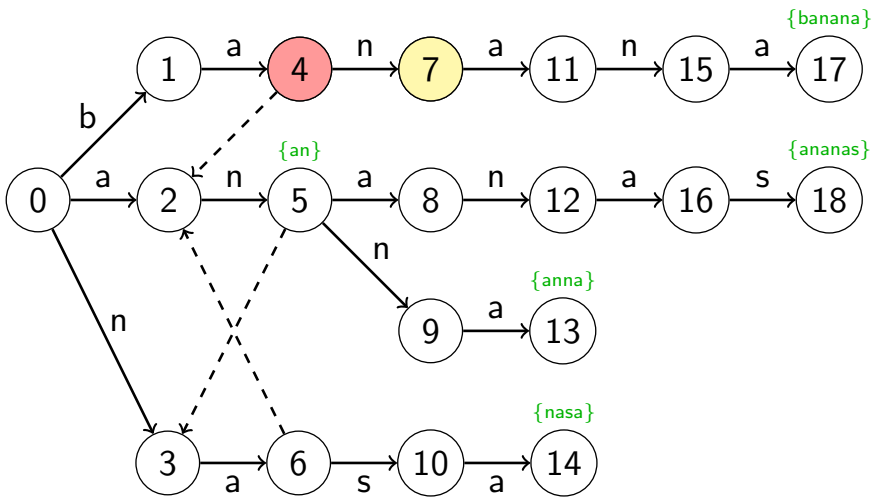

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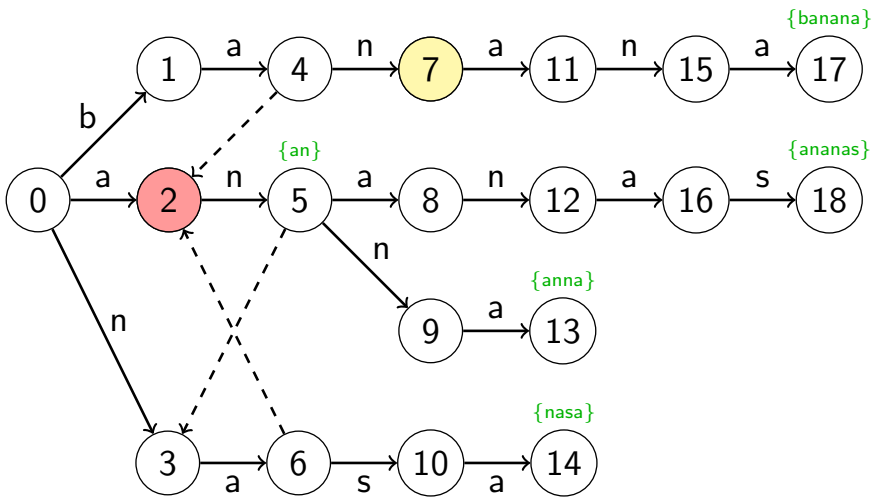

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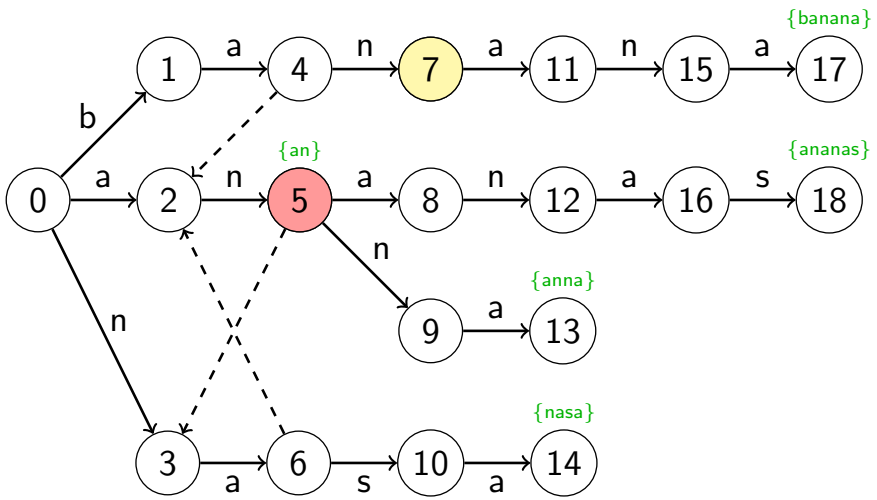

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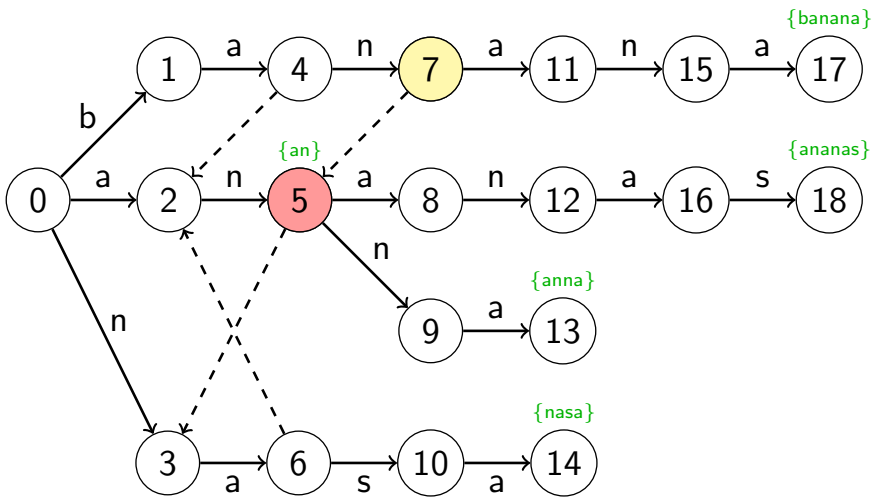

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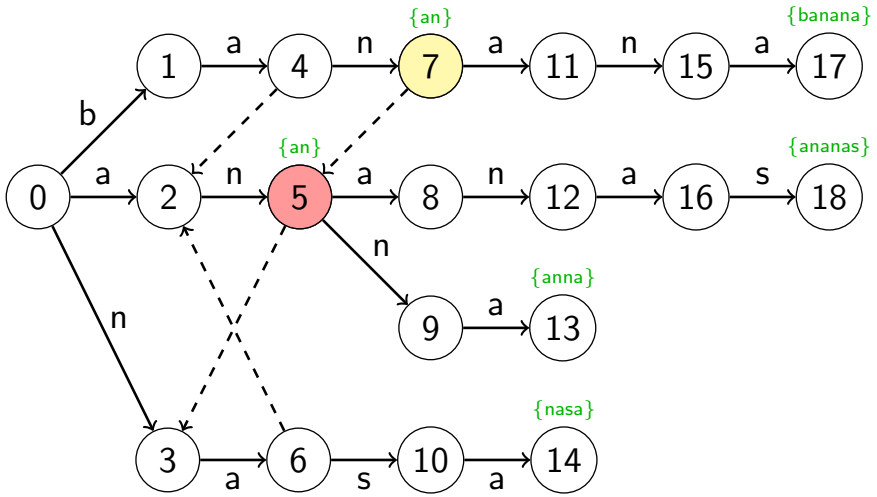

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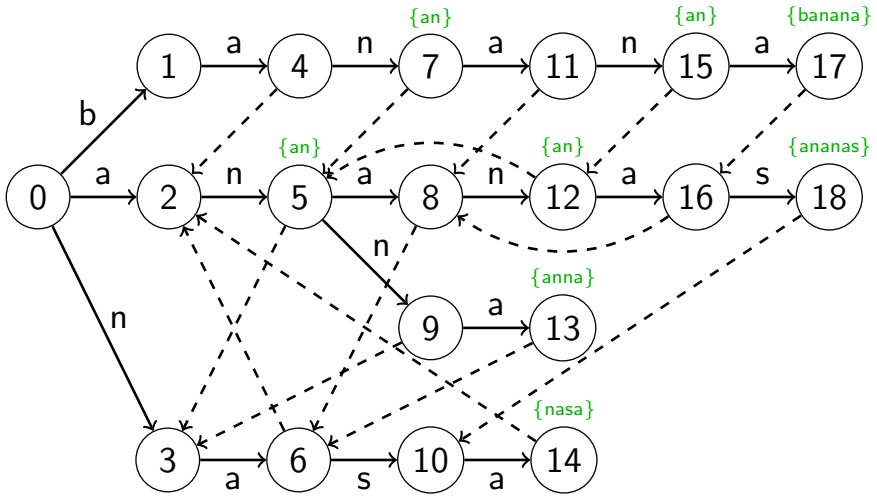

Der Aho-Corasick-Algorithmus

Mustersuche mit dem Aho-Corasick-Algorithmus:

```
1 def aho_corasick(P, T):
2     q = build_AC(P)
3     for (i, c) in enumerate(T):
4         q = delta(q, c)
5         for x in q.out:
6             yield (i-len(P[x])+1, i+1, x)
```

Laufzeitanalyse

- Wie beim KMP-Algorithmus wird die while-Schleife in der *delta*-Funktion amortisiert beim Erstellen des Automaten nur $\mathcal{O}(m)$ und bei der Mustersuche nur $\mathcal{O}(n)$ mal betreten.

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- Der AC-Algorithmus braucht zum Erstellen des Automaten, für die Mustersuche und das Erkennen von Zuständen mit nichtleerer Ausgabe $\mathcal{O}(m+n)$ Zeit.
- Die Ausgabe z kann pathologisch Größe $\mathcal{O}(kn)$ haben, insgesamt $\mathcal{O}(m+n+z)$ Zeit

Zusammenfassung

- Der Aho-Corasick-Algorithmus ist eine Erweiterung des KMP-Algorithmus auf eine Menge von Mustern.
- Laufzeit: $\mathcal{O}(m + n + z)$; dabei ist z die Größe der Ausgabe

Zusammenfassung

- Der Aho-Corasick-Algorithmus ist eine Erweiterung des KMP-Algorithmus auf eine Menge von Mustern.
- Laufzeit: $\mathcal{O}(m + n + z)$; dabei ist z die Größe der Ausgabe
- Bei der gezeigten Implementierung (konkatenierte Ausgabelisten) beträgt der Speicherplatz $O(n + km)$, bei einer Implementierung mit Verweisen nur $O(n + m)$.