Algorithms and Datastructures

Levenshtein distance, Dynamic programming

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Bioinformatics Group / Department of Computer Science

Algorithms and Datastructures, February 2018

Structure

Introduction

Edit distance

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Edit distance:

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- Measurement for similarity of two words / strings

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- Algorithm for efficient calculation

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- Measurement for similarity of two words / strings
- Algorithm for efficient calculation
- General principle: dynamic programming

BioInfSearch

ejafjatlajökuk

Search!

eyjafjallajökull
eyjafjallajökull movie
eyjafjallajälull trailer

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Wikipedia.org:

"Der Eyjafjallajökull (['eɪja,fjatla,jœ:kʏtl̥])[3], auf Deutsch Eyjafjöll-Gletscher, ist der sechstgrößte Gletscher Islands.

Er liegt an der äußersten Südküste, westlich des Gletschers Mýrdalsjökull in der Gemeinde Rangárþing eystra, die größte Höhe beträgt 1651 m. Unter dem Gletscher befindet sich der Vulkan Eyjafjöll mit eigener Magmakammer, der seit der Besiedelung von Island in den Jahren 920, 1612 (oder 1613), 1821 bis 1823 und zuletzt im Jahr 2010 aktiv war."

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- Duplicates in databases:

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Hein Blöd    27568 Bremerhaven
Hein Bloed   27568 Bremerhafen
Hein Doof    27478 Cuxhaven
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- Bioinformatics: Similarity of DNA-sequences

Search of similar proteins:

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- Changed life-science completely

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Search of similar proteins:

- `BLAST` (**B**asic **L**ocal **A**lignment **S**earch **T**ool)
- Alignment $\hat{=}$ Edit distance
- Changed life-science completely
- Cited 63437 times on Google Scholar (Sep. 2017)

Structure

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Definition of edit distance: (*Levenshtein-distance*)

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- Let x, y be two strings
- Edit distance $\mathrm{ED}(x,y)$ of x and y:
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  The minimal number of operations to transform x into y
  - `Insert` a character
  - `Replace` a character with another
  - `Delete` a character

Edit distance

Example

1 2 3 4 5
DOOF

B L OED

1 2 3 4 5
DOOF
↓ `replace(1, B)`
BOOF

B L O E D

Edit distance
Example

1 2 3 4 5
DOOF
$\downarrow$ `replace(1, B)`
BOOF
$\downarrow$ `replace(2, L)`
BLOF

BLOED

1 2 3 4 5
DOOF

$\downarrow$ `replace(1, B)`

BOOF

$\downarrow$ `replace(2, L)`

BLOF

$\downarrow$ `insert(4, E)`

BLOEF

BLOED

```
12345
DOOF
  ↓      replace(1, B)
BOOF
  ↓      replace(2, L)
BLOF
  ↓      insert(4, E)
BLOEF
  ↓      replace(5, D)
BLOED
```

Edit distance
Example

$$
\begin{array}{ll}
\text{1 2 3 4 5} & \\
\text{DOOF} & \\
\downarrow & \underbrace{\begin{array}{l}\texttt{replace(1, B)}\\ \\ \texttt{replace(2, L)}\\ \\ \texttt{insert(4, E)}\\ \\ \texttt{replace(5, D)}\end{array}}_{\text{ED=4}} \\
\text{BOOF} & \\
\downarrow & \\
\text{BLOF} & \\
\downarrow & \\
\text{BLOEF} & \\
\downarrow & \\
\text{BLOED} &
\end{array}
$$

```
12345
DOOF
  ↓     replace(1, B)
BOOF
  ↓     replace(2, L)
BLOF
  ↓     insert(4, E)
BLOEF
  ↓     replace(5, D)
BLOED
```

$\underbrace{\texttt{replace(1, B) replace(2, L) insert(4, E) replace(5, D)}}_{\text{ED}=4}$

12345
BLOED

Edit distance
Example

1 2 3 4 5
DOOF
↓ `replace(1, B)`
BOOF
↓ `replace(2, L)`
BLOF
↓ `insert(4, E)`
BLOEF
↓ `replace(5, D)`
BLOED

$\underbrace{\qquad\qquad\qquad\qquad}_{\text{ED=4}}$

1 2 3 4 5
B L OED

DOOF

Edit distance
Example

1 2 3 4 5	
DOOF	
↓	`replace(1, B)`
BOOF	
↓	`replace(2, L)`
BLOF	
↓	`insert(4, E)`
BLOEF	
↓	`replace(5, D)`
BLOED	
	ED=4

1 2 3 4 5	
B LOED	
↓	`replace(5, F)`
B LOEF	

DOOF

```
12345
DOOF
  ↓     replace(1, B)
BOOF
  ↓     replace(2, L)
BLOF
  ↓     insert(4, E)
BLOEF
  ↓     replace(5, D)
BLOED
```

$\underbrace{\hspace{8em}}_{\text{ED=4}}$

```
12345
BLOED
  ↓     replace(5, F)
BLOEF
  ↓     delete(4)
BLOF

DOOF
```

Edit distance
Example

1 2 3 4 5 DOOF		1 2 3 4 5 B LOED	
↓	`replace(1, B)`	↓	`replace(5, F)`
BOOF		B LOEF	
↓	`replace(2, L)`	↓	`delete(4)`
B LOF		B LOF	
↓	`insert(4, E)`	↓	`replace(2, O)`
B LOEF		B OOF	
↓	`replace(5, D)`		
B LOED		DOOF	

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Edit distance
Example

1 2 3 4 5		1 2 3 4 5	
DOOF		B LOED	
↓	`replace(1, B)`	↓	`replace(5, F)`
BOOF		B LOEF	
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B LOF		B LOF	
↓	`insert(4, E)`	↓	`replace(2, O)`
B LOEF		B OOF	
↓	`replace(5, D)`	↓	`replace(1, D)`
B LOED		DOOF	

$$\underbrace{\qquad\qquad\qquad\qquad}_{\text{ED=4}}$$

12345		12345	
DOOF		BLOED	
↓	`replace(1, B)`	↓	`replace(5, F)`
BOOF		BLOEF	
↓	`replace(2, L)`	↓	`delete(4)`
BLOF		BLOF	
↓	`insert(4, E)`	↓	`replace(2, O)`
BLOEF		BOOF	
↓	`replace(5, D)`	↓	`replace(1, D)`
BLOED		DOOF	
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- $x[i..j]$ is the slice of x from i to j where $1 \leq i \leq j \leq |x|$

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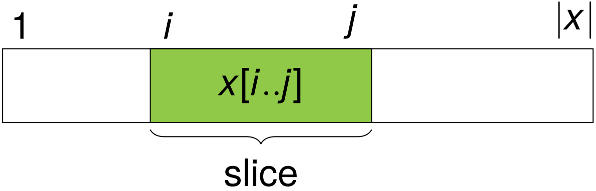

Edit distance

Trivial facts:

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- $\mathrm{ED}(x,y) = \mathrm{ED}(y,x)$
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- $\mathrm{ED}(x,y) \geq \mathrm{abs}(|x| - |y|)$

$$\mathrm{abs}(x) = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{else} \end{cases}$$

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Trivial facts:

- $\mathrm{ED}(x,y) = \mathrm{ED}(y,x)$
- $\mathrm{ED}(x,\varepsilon) = |x|$
- $\mathrm{ED}(x,y) \geq \mathrm{abs}(|x| - |y|)$ $\qquad \mathrm{abs}(x) = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{else} \end{cases}$
- $\mathrm{ED}(x,y) \leq \mathrm{ED}(x[1..n-1], y[1..m-1]) + 1$ $\qquad n = |x|,\ m = |y|$

Solutions based on examples:

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- From VERIEN to FERIEN?

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- Searching biggest substrings can yield the solution but doesn't have to

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Recursive approach:

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Recursive approach:

- Dividing in two halves? Not a good idea:

$\mathrm{ED}(GRAU, RAUM) = 2$ but $\mathrm{ED}(GR, RA) + \mathrm{ED}(AU, UM) = 4$

Edit distance
Solving examples

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Recursive approach:

- Dividing in two halves? Not a good idea:

  $\mathrm{ED}(GRAU, RAUM) = 2$ but $\mathrm{ED}(GR, RA) + \mathrm{ED}(AU, UM) = 4$

- Finding „smaller“ sub problems?
  Let's try it!

Edit distance

Terminology:

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- Let x, y be two strings

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Terminology:

- Let x, y be two strings
- Let $\sigma_1, \ldots, \sigma_k$ be a sequence of k operations where $k = \mathrm{ED}(x, y)$ for $x \to y$ (transform x into y)
  (We do not know this sequence but we assume it exists)

Edit distance

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Terminology:

- We only consider monotonous sequences:
  The posititon of σ_{i+1} is $\geq$ the position of σ_i where we only allow the positions to be equal on a `delete` operation

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1 2 3 4 5		1 2 3 4 5 6 7	
DOOF		SAUDOOF	
$\downarrow$	`replace(1, B)`	$\downarrow$	`delete(1)`
BOOF		AUDOOF	
$\downarrow$	`replace(2, L)`	$\downarrow$	`delete(1)`
BLOF		UDOOF	
$\downarrow$	insert(4, E)	$\downarrow$	`delete(1)`
BLOEF		DOOF	
$\downarrow$	`replace(5, D)`	$\downarrow$	`insert(4, O)`
BLOED		DOOOF	

Edit distance

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BLOEF			DOOF	
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BLOED			DOOOF	

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- **Lemma:** For any x and y with $k = \mathrm{ED}(x, y)$ exists a monotonous sequence of k operations for $x \rightarrow y$
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1	2	3	4	5
D	O	O	F	
B	L	O	E	D

1	2	3	4	5	6	7
S	A	U	D	O	O	F
D	O	O	O	F		

Consider the last operation:

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- Solve blue part recursively

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- Solve blue part recursively

DOOF
$\downarrow\downarrow\downarrow\downarrow$
BLOE
$\downarrow$`insert`
BLOED

Abbildung: Case 1a

DOOF
$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow$
BLOEDF
$\downarrow$`delete`
BLOED

Abbildung: Case 1b

DOOF
$\downarrow\downarrow\downarrow\downarrow\downarrow$
BLOEF
$\downarrow$`replace`
BLOED

Abbildung: Case 1c

Consider the last operation:

Consider the last operation:

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Edit distance
Recursive approach

Consider the last operation:

- Solve blue part recursively

WINTER
$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow$
SOMMER
$\downarrow$nothing
SOMMER

Abbildung: Case 2

Display of solution:

- Alignment
- Example:

_	_	_	B	L	O	E	D
S	A	U	B	L	O	E	D

Dynamic programming:

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- Instances of Bellman's principle of optimality:

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Dynamic programming:

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Dynamic programming:

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Abbildung: Richard Bellman (1920 - 1984)

- Optimal solutions consist of optimal partial solutions
  - Shortest paths: Each partial path has to be optimal
  - Edit distance: Each partial alignment has to be optimal

- Always solvable through dynamic programming (Caching of optimal partial solutions)

Edit distance

Case analysis:

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  - $\sigma_1, \ldots, \sigma_{k-1}$: $x \to z$ and σ_k: $z \to y$
    Example:

$$x = \text{DOOF},\ z = \text{SAUBLOEF},\ y = \text{SAUBLOED}$$

Edit distance

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  - Let $n = |x|$, $m = |y|$, $m' = |z|$

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    Example:

$$x = \mathrm{DOOF},\ z = \mathrm{SAUBLOEF},\ y = \mathrm{SAUBLOED}$$

  - Let $n = |x|$, $m = |y|$, $m' = |z|$
  - We note $m' \in \{m-1, m, m+1\}$ why?

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  - Case 1a: $\sigma_k = \texttt{insert}(m'+1, y[m])$ [then $m' = m-1$]
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  - Case 1c: $\sigma_k = \texttt{replace}(m', y[m])$ [then $m' = m$]

- Case 2: σ_k does nothing at the outer end:
  - Then $z[m'] = y[m]$ and $x[n'] = z[m']$ and with that $\sigma_1, \ldots, \sigma_{k-1}$: $x[1..n-1] \rightarrow y[1..m-1]$ and $x[n] = y[m]$

Edit distance

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- Case 1a (`insert`): $\sigma_1, \ldots, \sigma_{k-1} \colon x \qquad \rightarrow y[1..m-1]$

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Edit distance

Case analysis:

- Case 1a (`insert`): $\sigma_1,\ldots,\sigma_{k-1}: x \rightarrow y[1..m-1]$
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This results in the recursive formula:

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  - $\mathrm{ED}(x, y[1..m-1]) + 1$ and

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- Case 1a (`insert`): $\sigma_1, \dots, \sigma_{k-1}$: $x \rightarrow y[1..m-1]$
- Case 1b (`delete`): $\sigma_1, \dots, \sigma_{k-1}$: $x[1..n-1] \rightarrow y$
- Case 1c (`replace`): $\sigma_1, \dots, \sigma_{k-1}$: $x[1..n-1] \rightarrow y[1..m-1]$
- Case 2 (`nothing`): $\sigma_1, \dots, \sigma_k$: $x[1..n-1] \rightarrow y[1..m-1]$

This results in the recursive formula:

- For $|x| > 0$ and $|y| > 0$ is $\mathrm{ED}(x,y)$ the minimum of
  - $\mathrm{ED}(x, y[1..m-1]) + 1$ and
  - $\mathrm{ED}(x[1..n-1], y) + 1$ and

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Edit distance

Case analysis:

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  - $\mathrm{ED}(x[1..n-1], y[1..m-1]) + 0$ if $x[n] = y[m]$

Edit distance

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  - $\mathrm{ED}(x[1..n-1], y[1..m-1]) + 1$ if $x[n] \neq y[m]$
  - $\mathrm{ED}(x[1..n-1], y[1..m-1]) + 0$ if $x[n] = y[m]$
- For $|x| = 0$ is $\mathrm{ED}(x,y) = |y|$

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Case analysis:

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- Case 1b (`delete`): $\sigma_1, \ldots, \sigma_{k-1}\colon x[1..n-1] \rightarrow y$
- Case 1c (`replace`): $\sigma_1, \ldots, \sigma_{k-1}\colon x[1..n-1] \rightarrow y[1..m-1]$
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  - $\mathrm{ED}(x[1..n-1], y[1..m-1]) + 0$ if $x[n] = y[m]$
- For $|x| = 0$ is $\mathrm{ED}(x,y) = |y|$
- For $|y| = 0$ is $\mathrm{ED}(x,y) = |x|$

```python
def edit_distance(x, y):
    if len(x) == 0:
        return len(y)
    if len(y) == 0:
        return len(x)

    ed1 = edit_distance(x, y[:-1]) + 1
    ed2 = edit_distance(x[:-1], y) + 1
    ed3 = edit_distance(x[:-1], y[:-1])
    if x[-1] != y[-1]:
        ed3 += 1

    return min(ed1, ed2, ed3)
```

Recursive program:

Recursive program:

- The algorithm results in the following recursive formular:

$$
\begin{aligned}
T(n,m) &= T(n-1,m) + T(n,m-1) + T(n-1,m-1) + 1 \\
&\geq T(n-1,m-1) + T(n-1,m-1) + T(n-1,m-1) \\
&= 3 \cdot T(n-1,m-1)
\end{aligned}
$$

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$$\begin{aligned} T(n,m) &= T(n-1,m) + T(n,m-1) + T(n-1,m-1) + 1 \\ &\geq T(n-1,m-1) + T(n-1,m-1) + T(n-1,m-1) \\ &= 3 \cdot T(n-1,m-1) \end{aligned}$$

- This results in $T(n,n) \geq 3^n$

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&= 3 \cdot T(n-1,m-1)
\end{aligned}
$$

- This results in $T(n,n) \geq 3^n$

$\Rightarrow$ The runtime is at least exponential

Dynamic programming:

Edit distance

Dynamic programming:

- We create a table with all possible combination of substrings and save calculated entries
- This results in a runtime and space consumption of $O(n \cdot m)$

Edit distance

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Visualization on the next slide:

Edit distance

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- We create a table with all possible combination of substrings and save calculated entries
- This results in a runtime and space consumption of $O(n \cdot m)$

Visualization on the next slide:

- Operations always refer to the last position (indices are omitted)

Edit distance

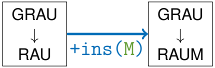
Dynamic programming:

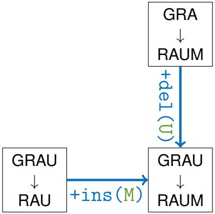
- We create a table with all possible combination of substrings and save calculated entries
- This results in a runtime and space consumption of $O(n \cdot m)$

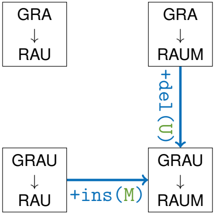
Visualization on the next slide:

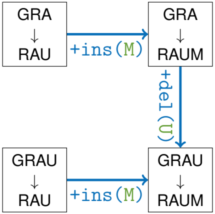
- Operations always refer to the last position (indices are omitted)
- We also display the replaced character on a `replace` operation to visualize operations without costs
  $\Rightarrow$ `repl(A, A)`

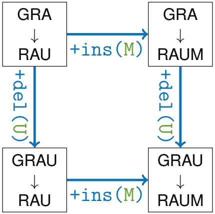
GRAU
↓
RAUM

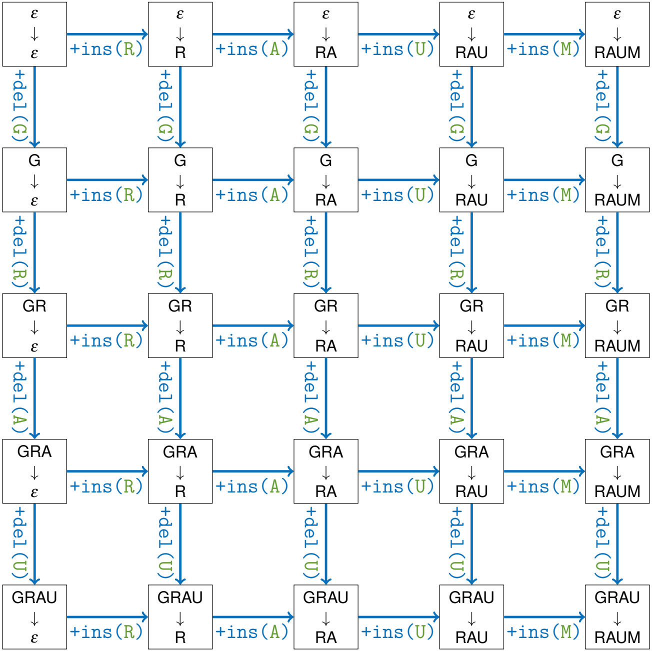

GRAU
↓
RAU
+ins(M)
GRAU
↓
RAUM


GRA
↓
RAUM
+del(U)
GRAU
↓
RAU
+ins(M)
GRAU
↓
RAUM

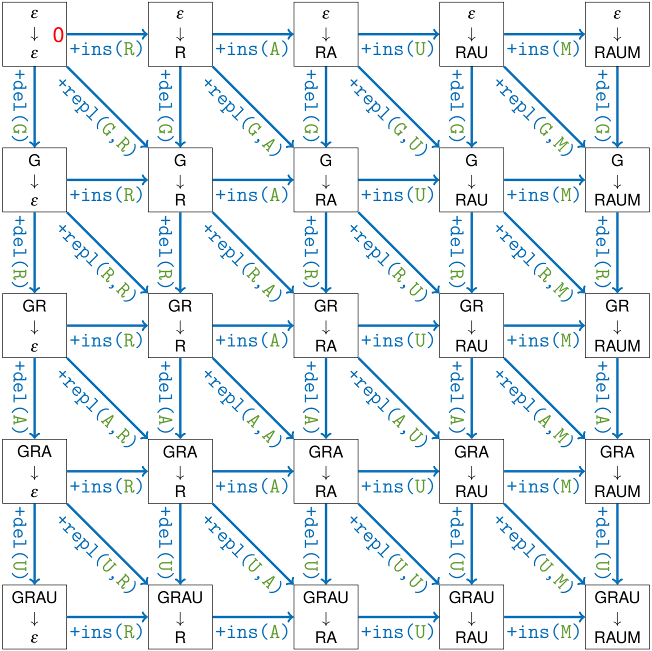

GRA
↓
RAU
GRA
↓
RAUM
+del(U)
GRAU
↓
RAU
+ins(M)
GRAU
↓
RAUM


GRA ↓ RAU
+ins(M)
GRA ↓ RAUM
+del(U)
GRAU ↓ RAU
+ins(M)
GRAU ↓ RAUM

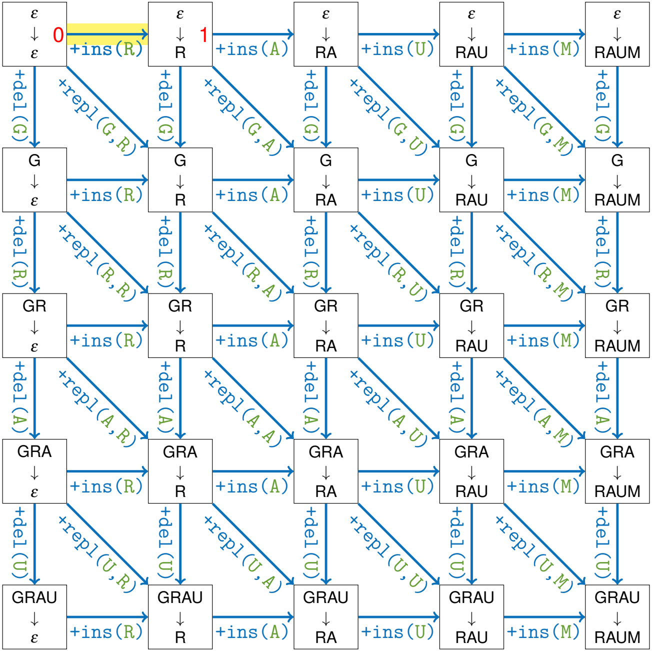

GRA
↓
RAU
+ins(M)
GRA
↓
RAUM
+del(U)
+del(U)
GRAU
↓
RAU
+ins(M)
GRAU
↓
RAUM


ε ↓ ε
+ins(R)
ε ↓ R
+ins(A)
ε ↓ RA
+ins(U)
ε ↓ RAU
+ins(M)
ε ↓ RAUM
+del(G)
G ↓ ε
+ins(R)
G ↓ R
+ins(A)
G ↓ RA
+ins(U)
G ↓ RAU
+ins(M)
G ↓ RAUM
+del(R)
GR ↓ ε
+ins(R)
GR ↓ R
+ins(A)
GR ↓ RA
+ins(U)
GR ↓ RAU
+ins(M)
GR ↓ RAUM
+del(A)
GRA ↓ ε
+ins(R)
GRA ↓ R
+ins(A)
GRA ↓ RA
+ins(U)
GRA ↓ RAU
+ins(M)
GRA ↓ RAUM
+del(U)
GRAU ↓ ε
+ins(R)
GRAU ↓ R
+ins(A)
GRAU ↓ RA
+ins(U)
GRAU ↓ RAU
+ins(M)
GRAU ↓ RAUM

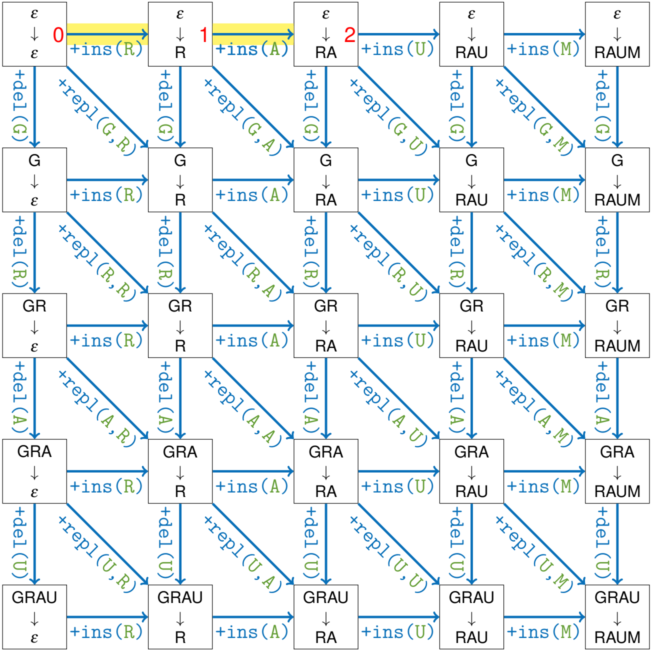
Fast algorithm:
We can determine the edit distance for all combination of partial strings from the top left to bottom right.

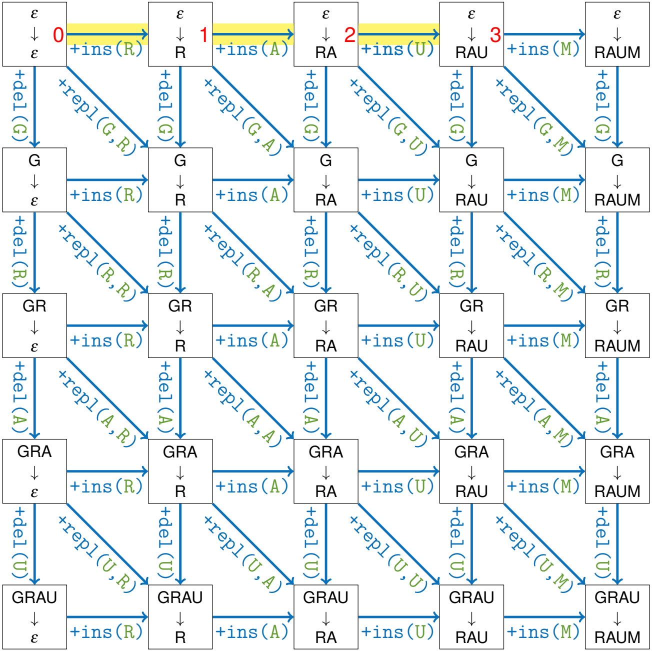


ε ↓ ε
0
ε ↓ R
ε ↓ RA
ε ↓ RAU
ε ↓ RAUM
G ↓ ε
G ↓ R
G ↓ RA
G ↓ RAU
G ↓ RAUM
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
+del(A)
+del(U)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)

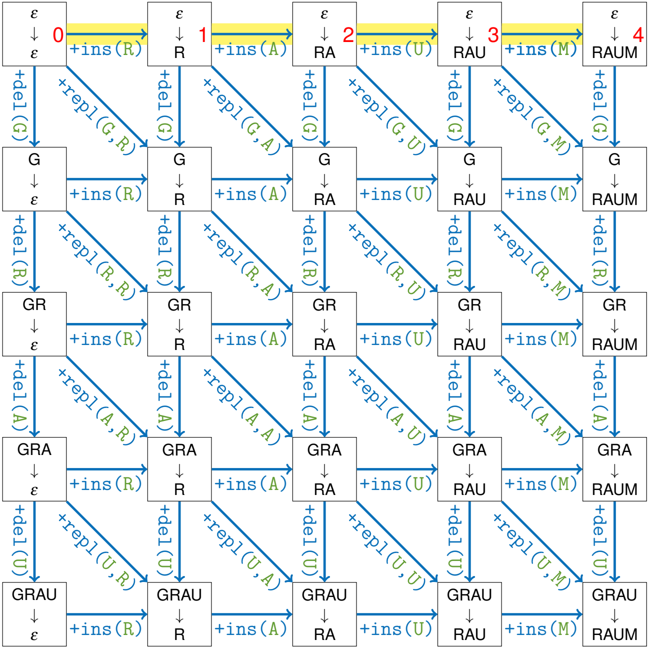


ε ↓ ε
0
+ins(R)
ε ↓ R
1
+ins(A)
ε ↓ RA
+ins(U)
ε ↓ RAU
+ins(M)
ε ↓ RAUM
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε
G ↓ R
G ↓ RA
G ↓ RAU
G ↓ RAUM
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM

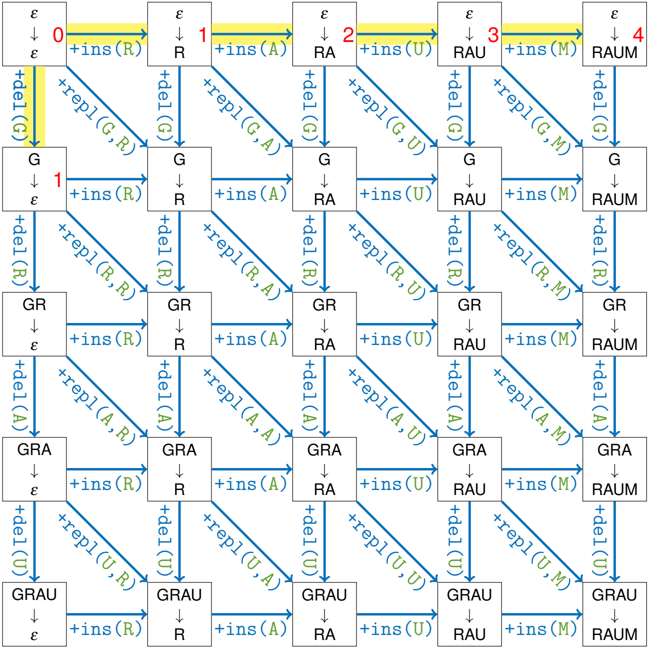

ε ↓ ε
0
+ins(R)
ε ↓ R
1
+ins(A)
ε ↓ RA
2
+ins(U)
ε ↓ RAU
+ins(M)
ε ↓ RAUM
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε
G ↓ R
G ↓ RA
G ↓ RAU
G ↓ RAUM
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM

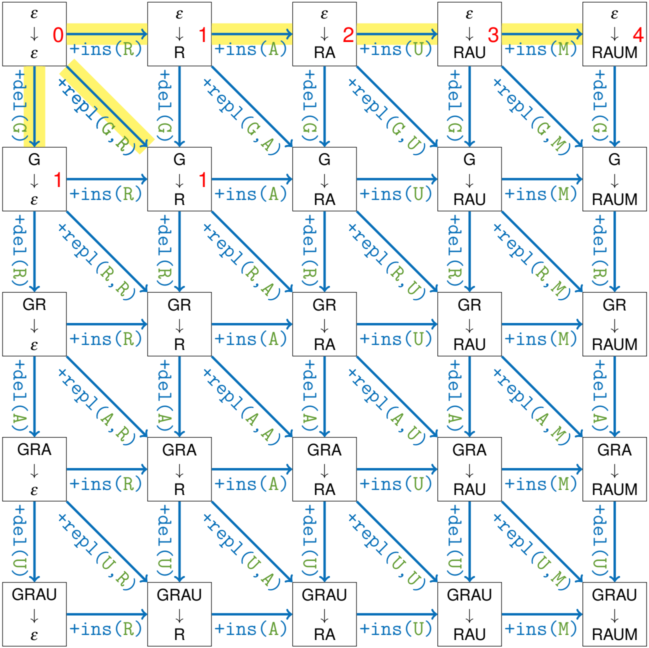


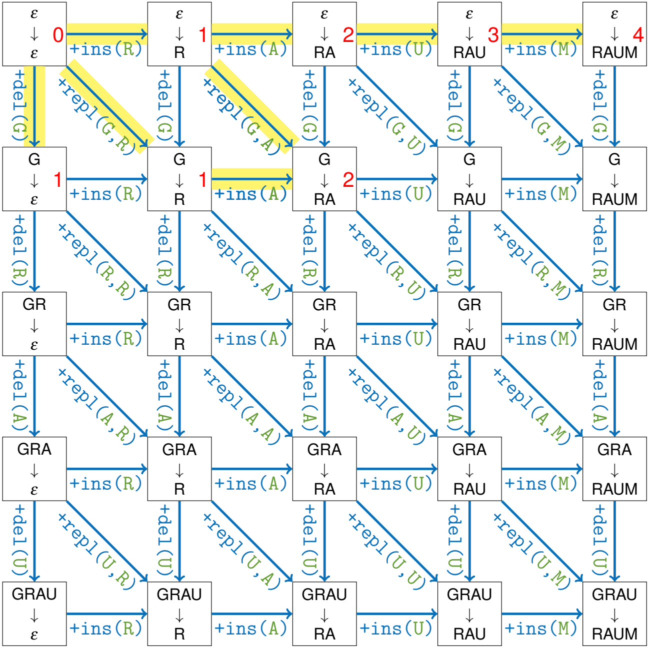
0
1
2
3
ε ↓ ε
+ins(R)
ε ↓ R
+ins(A)
ε ↓ RA
+ins(U)
ε ↓ RAU
+ins(M)
ε ↓ RAUM
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε
G ↓ R
G ↓ RA
G ↓ RAU
G ↓ RAUM
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM

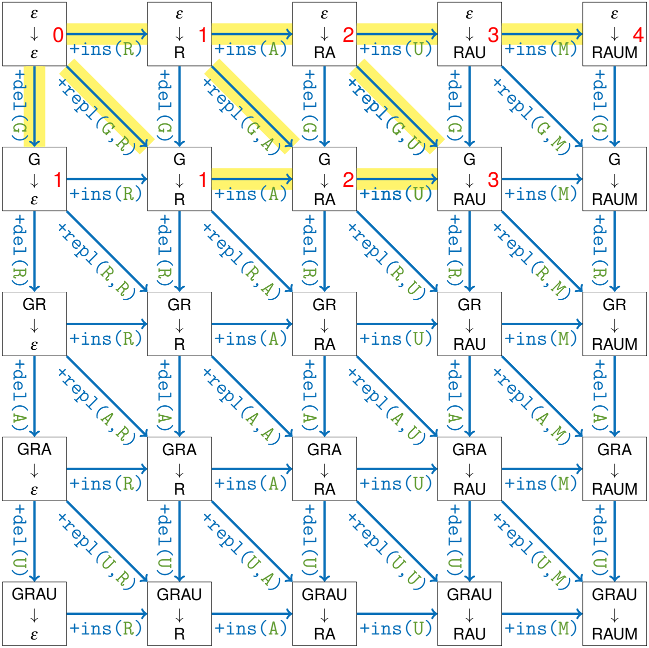


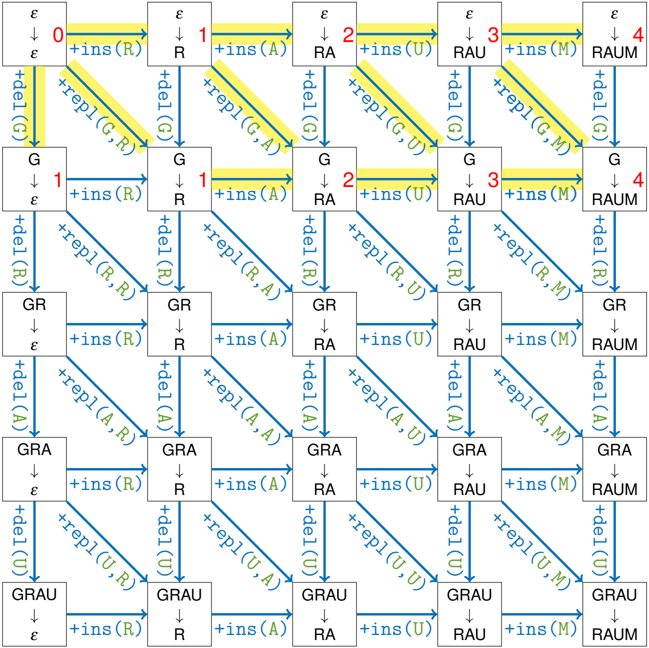
ε → ε
ε → R
ε → RA
ε → RAU
ε → RAUM
0
1
2
3
4
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
+del(A)
+del(U)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
G → ε
G → R
G → RA
G → RAU
G → RAUM
GR → ε
GR → R
GR → RA
GR → RAU
GR → RAUM
GRA → ε
GRA → R
GRA → RA
GRA → RAU
GRA → RAUM
GRAU → ε
GRAU → R
GRAU → RA
GRAU → RAU
GRAU → RAUM

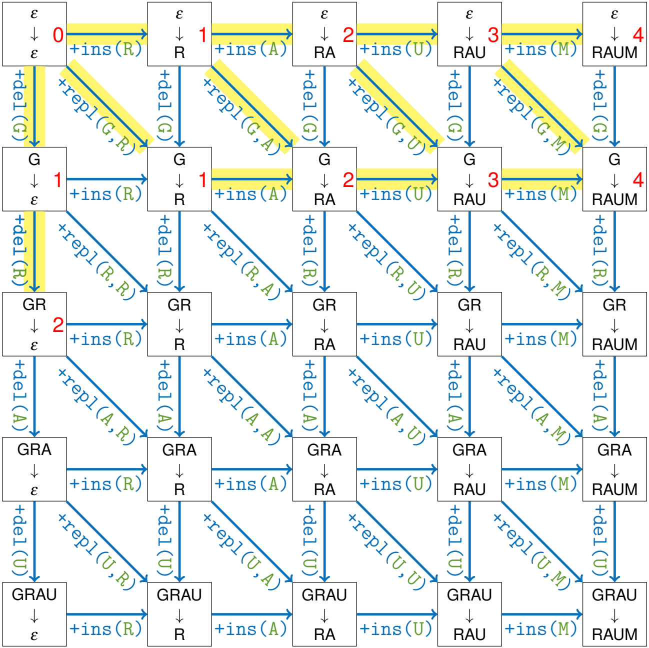

ε ↓ ε
ε ↓ R
ε ↓ RA
ε ↓ RAU
ε ↓ RAUM
0
1
2
3
4
1
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
+del(A)
+del(U)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
G ↓ ε
G ↓ R
G ↓ RA
G ↓ RAU
G ↓ RAUM
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM

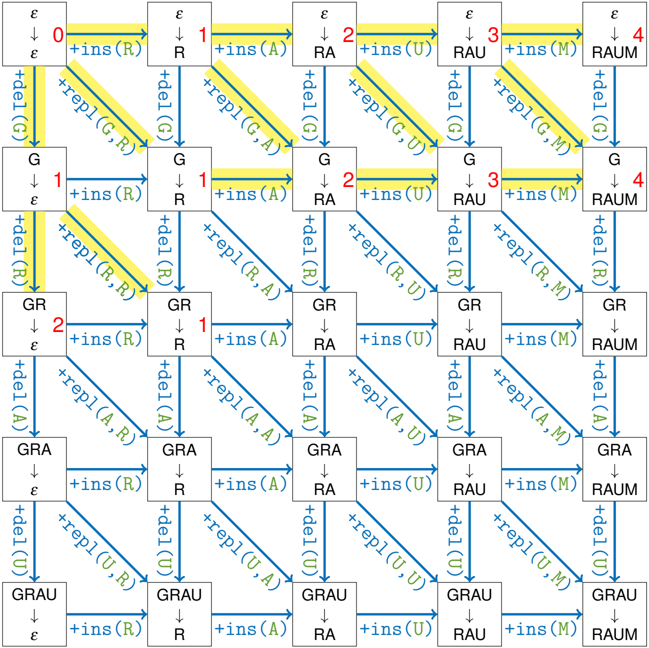

ε ↓ ε 0
+ins(R)
ε ↓ R 1
+ins(A)
ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G) +repl(G,R) +del(G) +repl(G,A) +del(G) +repl(G,U) +del(G) +repl(G,M) +del(G)
G ↓ ε 1
+ins(R)
G ↓ R 1
+ins(A)
G ↓ RA
+ins(U)
G ↓ RAU
+ins(M)
G ↓ RAUM
+del(R) +repl(R,R) +del(R) +repl(R,A) +del(R) +repl(R,U) +del(R) +repl(R,M) +del(R)
GR ↓ ε
+ins(R)
GR ↓ R
+ins(A)
GR ↓ RA
+ins(U)
GR ↓ RAU
+ins(M)
GR ↓ RAUM
+del(A) +repl(A,R) +del(A) +repl(A,A) +del(A) +repl(A,U) +del(A) +repl(A,M) +del(A)
GRA ↓ ε
+ins(R)
GRA ↓ R
+ins(A)
GRA ↓ RA
+ins(U)
GRA ↓ RAU
+ins(M)
GRA ↓ RAUM
+del(U) +repl(U,R) +del(U) +repl(U,A) +del(U) +repl(U,U) +del(U) +repl(U,M) +del(U)
GRAU ↓ ε
+ins(R)
GRAU ↓ R
+ins(A)
GRAU ↓ RA
+ins(U)
GRAU ↓ RAU
+ins(M)
GRAU ↓ RAUM


ε ↓ ε
0
+ins(R)
ε ↓ R
1
+ins(A)
ε ↓ RA
2
+ins(U)
ε ↓ RAU
3
+ins(M)
ε ↓ RAUM
4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε
1
G ↓ R
1
G ↓ RA
2
G ↓ RAU
G ↓ RAUM
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε
GR ↓ R
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM


ε → ε 0
ε → R 1
ε → RA 2
ε → RAU 3
ε → RAUM 4
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G → ε 1
G → R 1
G → RA 2
G → RAU 3
G → RAUM
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR → ε
GR → R
GR → RA
GR → RAU
GR → RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA → ε
GRA → R
GRA → RA
GRA → RAU
GRA → RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU → ε
GRAU → R
GRAU → RA
GRAU → RAU
GRAU → RAUM


ε → ε 0
+ins(R)
ε → R 1
+ins(A)
ε → RA 2
+ins(U)
ε → RAU 3
+ins(M)
ε → RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G → ε 1
G → R 1
G → RA 2
G → RAU 3
G → RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR → ε
GR → R
GR → RA
GR → RAU
GR → RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA → ε
GRA → R
GRA → RA
GRA → RAU
GRA → RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU → ε
GRAU → R
GRAU → RA
GRAU → RAU
GRAU → RAUM


ε → ε 0
+ins(R)
ε → R 1
+ins(A)
ε → RA 2
+ins(U)
ε → RAU 3
+ins(M)
ε → RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G → ε 1
G → R 1
G → RA 2
G → RAU 3
G → RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR → ε 2
GR → R
GR → RA
GR → RAU
GR → RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA → ε
GRA → R
GRA → RA
GRA → RAU
GRA → RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU → ε
GRAU → R
GRAU → RA
GRAU → RAU
GRAU → RAUM


ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA
GR ↓ RAU
GR ↓ RAUM
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
+del(A)
+del(U)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
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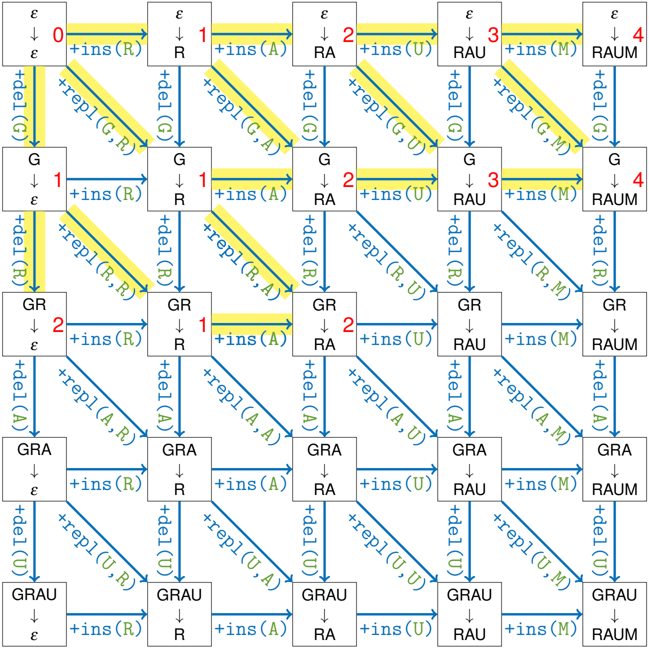
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)



ε → ε 0
ε → R 1
ε → RA 2
ε → RAU 3
ε → RAUM 4
G → ε 1
G → R 1
G → RA 2
G → RAU 3
G → RAUM 4
GR → ε 2
GR → R 1
GR → RA 2
GR → RAU
GR → RAUM
GRA → ε
GRA → R
GRA → RA
GRA → RAU
GRA → RAUM
GRAU → ε
GRAU → R
GRAU → RA
GRAU → RAU
GRAU → RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
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+del(R)
+del(A)
+del(U)
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+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
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+repl(U,U)
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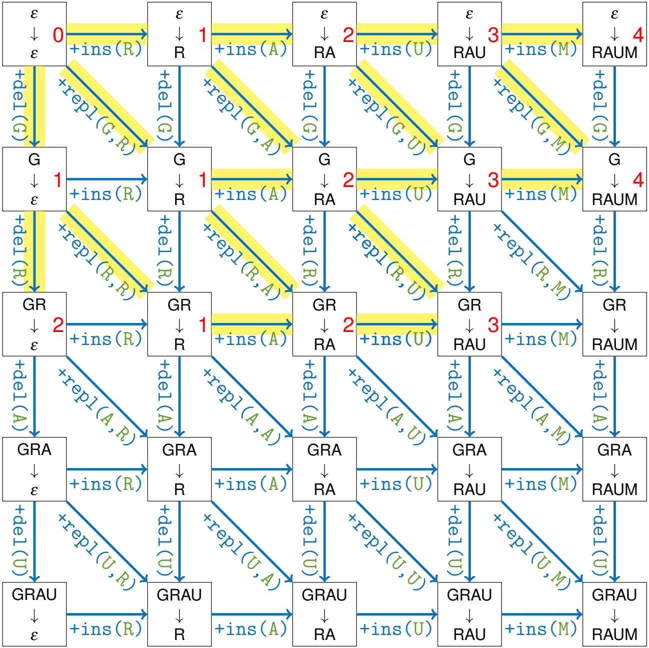
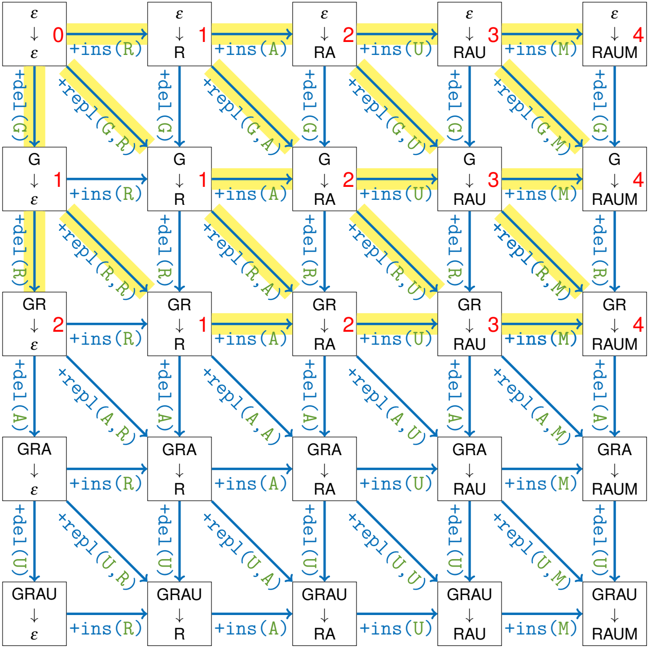
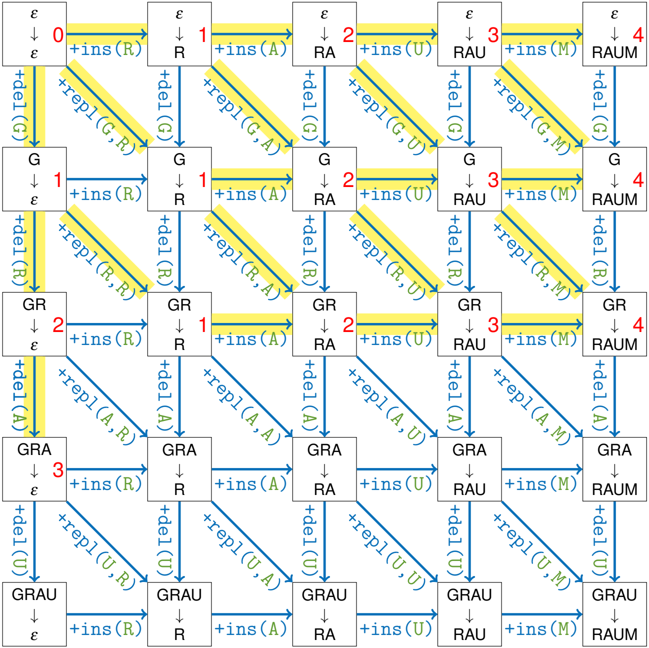
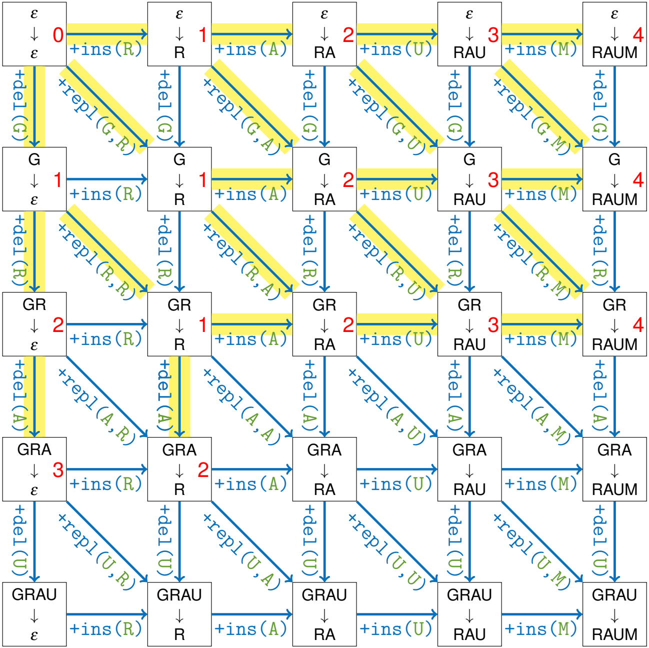

ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM

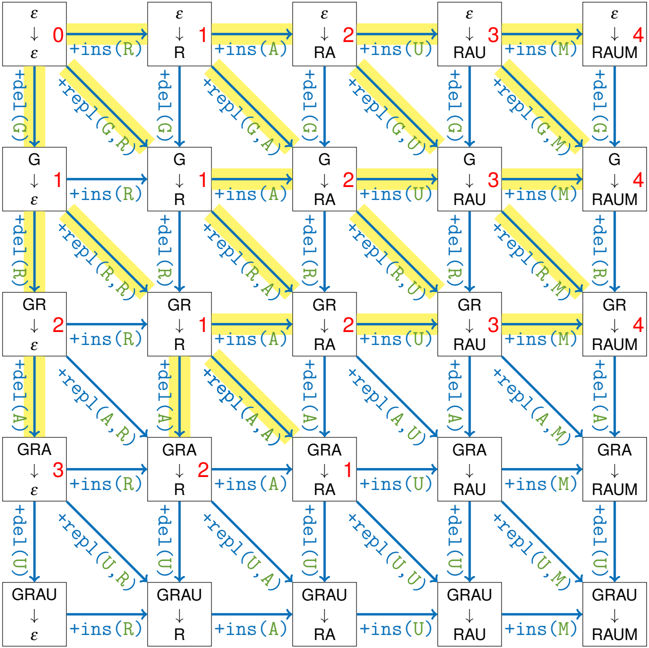


ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
+ins(R) +ins(A) +ins(U) +ins(M)
+del(G) +repl(G,R) +repl(G,A) +repl(G,U) +repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R) +repl(R,R) +repl(R,A) +repl(R,U) +repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A) +repl(A,R) +repl(A,A) +repl(A,U) +repl(A,M)
GRA ↓ ε
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U) +repl(U,R) +repl(U,A) +repl(U,U) +repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM


ε ↓ ε 0
+ins(R)
ε ↓ R 1
+ins(A)
ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε 3
GRA ↓ R
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM



ε ↓ ε 0
+ins(R)
ε ↓ R 1
+ins(A)
ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA
GRA ↓ RAU
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM


ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU
GRA ↓ RAUM
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
+del(A)
+del(U)
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+repl(G,A)
+repl(G,U)
+repl(G,M)
+repl(R,R)
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+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
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+repl(U,U)
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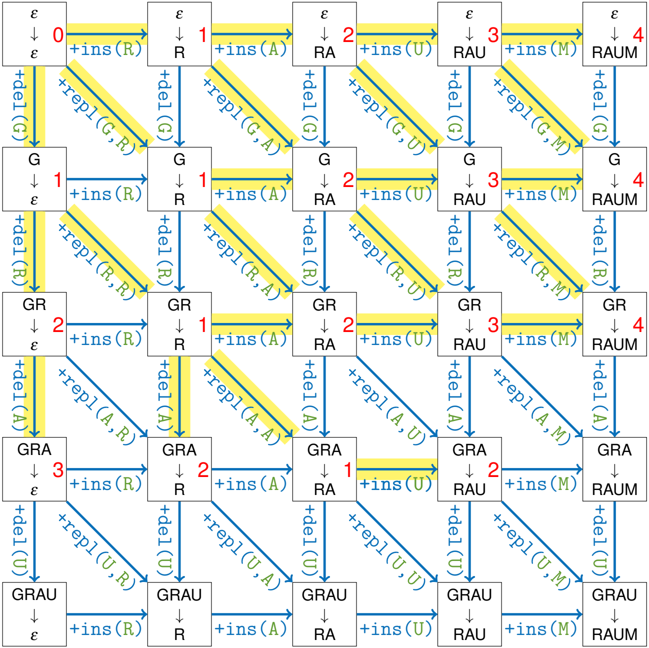
ε ↓ ε 0
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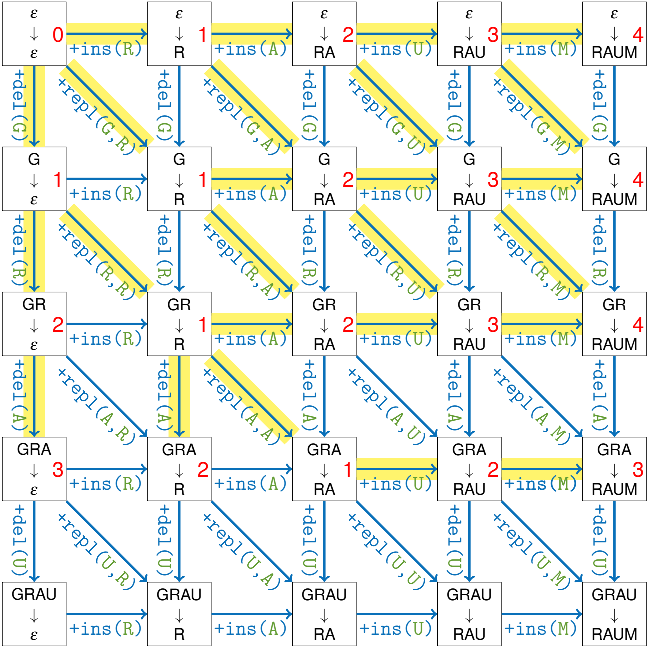
ε ↓ R 1
+ins(A)
ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM



ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
GRAU ↓ ε
GRAU ↓ R
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
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+del(R)
+del(A)
+del(U)
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+repl(G,M)
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+repl(U,A)
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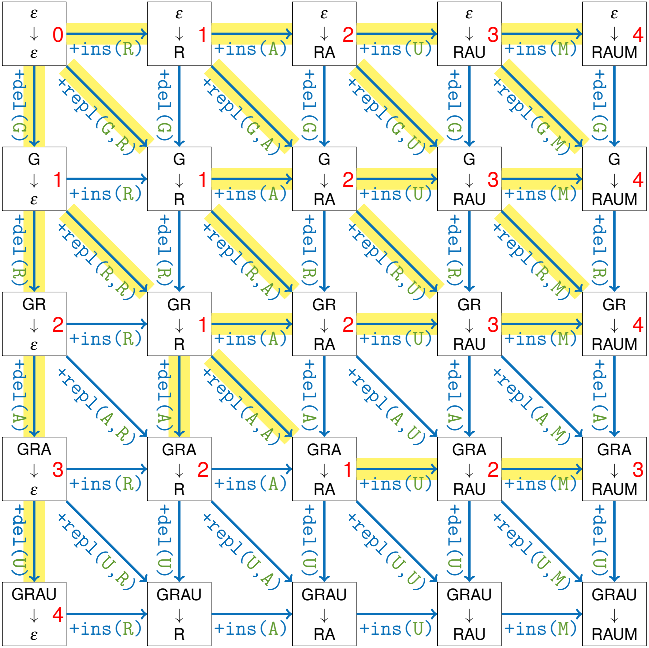
ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
GRAU ↓ ε 4
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GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM
+ins(R)
+ins(A)
+ins(U)
+ins(M)
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+del(R)
+del(A)
+del(U)
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+repl(G,M)
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+repl(R,M)
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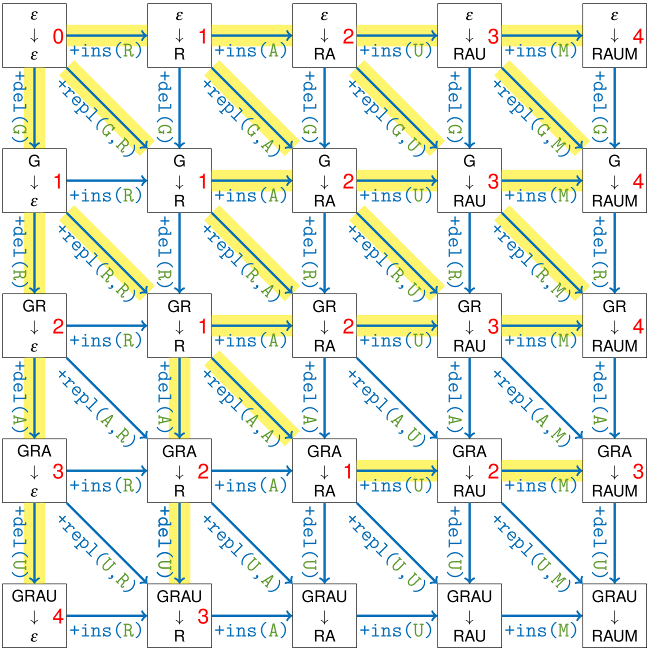
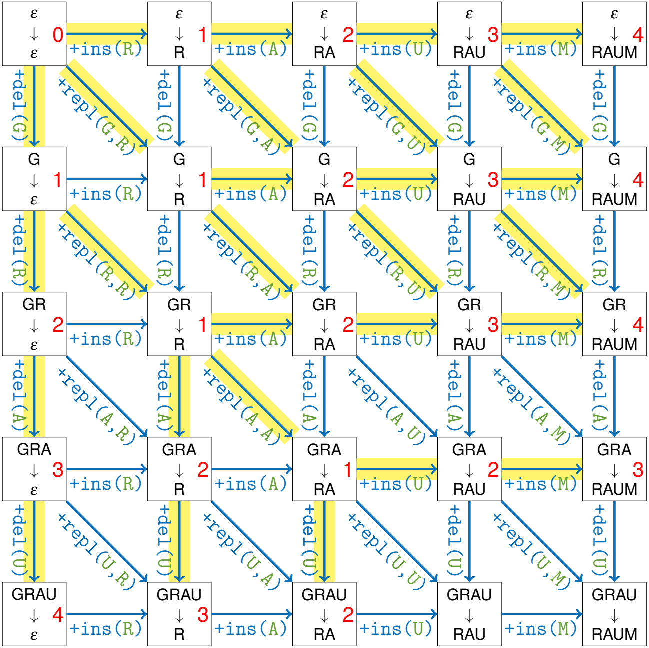


ε ↓ ε 0
+ins(R)
ε ↓ R 1
+ins(A)
ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
+del(U)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)
GRAU ↓ ε 4
GRAU ↓ R 3
GRAU ↓ RA
GRAU ↓ RAU
GRAU ↓ RAUM



ε ↓ ε 0
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ε ↓ R 1
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ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
+del(G)
+repl(G,R)
+repl(G,A)
+repl(G,U)
+repl(G,M)
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
+del(R)
+repl(R,R)
+repl(R,A)
+repl(R,U)
+repl(R,M)
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
+del(U)
+repl(U,R)
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+repl(U,U)
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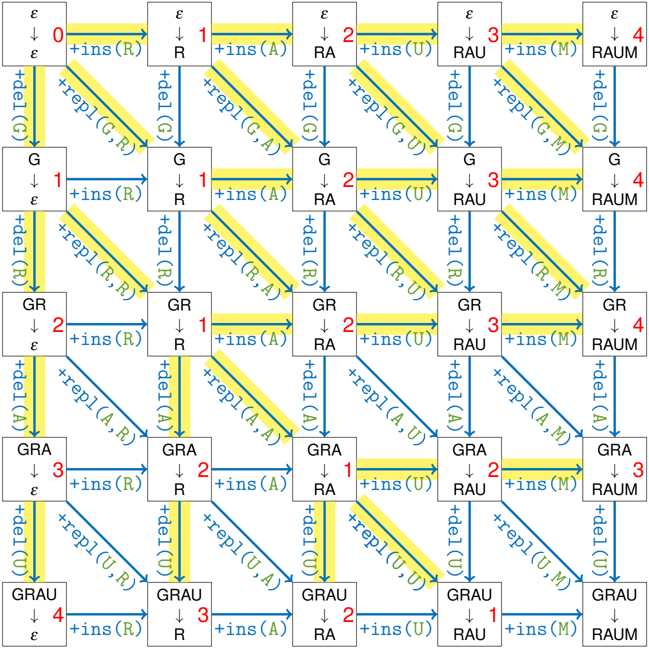
GRAU ↓ ε 4
GRAU ↓ R 3
GRAU ↓ RA 2
GRAU ↓ RAU
GRAU ↓ RAUM



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ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
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G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
GRAU ↓ ε 4
GRAU ↓ R 3
GRAU ↓ RA 2
GRAU ↓ RAU 1
GRAU ↓ RAUM
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+ins(U)
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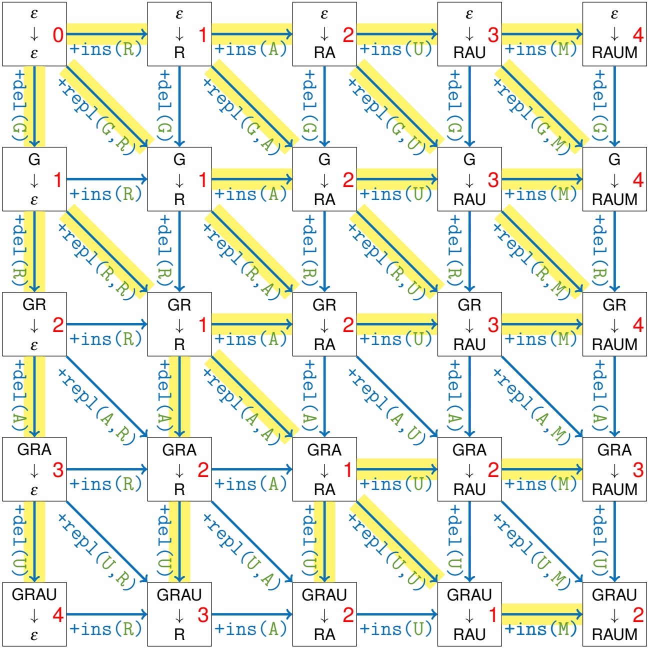

ε ↓ ε 0
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ε ↓ R 1
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ε ↓ RA 2
+ins(U)
ε ↓ RAU 3
+ins(M)
ε ↓ RAUM 4
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+repl(G,R)
+del(G)
+repl(G,A)
+del(G)
+repl(G,U)
+del(G)
+repl(G,M)
+del(G)
G ↓ ε 1
+ins(R)
G ↓ R 1
+ins(A)
G ↓ RA 2
+ins(U)
G ↓ RAU 3
+ins(M)
G ↓ RAUM 4
+del(R)
+repl(R,R)
+del(R)
+repl(R,A)
+del(R)
+repl(R,U)
+del(R)
+repl(R,M)
+del(R)
GR ↓ ε 2
+ins(R)
GR ↓ R 1
+ins(A)
GR ↓ RA 2
+ins(U)
GR ↓ RAU 3
+ins(M)
GR ↓ RAUM 4
+del(A)
+repl(A,R)
+del(A)
+repl(A,A)
+del(A)
+repl(A,U)
+del(A)
+repl(A,M)
+del(A)
GRA ↓ ε 3
+ins(R)
GRA ↓ R 2
+ins(A)
GRA ↓ RA 1
+ins(U)
GRA ↓ RAU 2
+ins(M)
GRA ↓ RAUM 3
+del(U)
+repl(U,R)
+del(U)
+repl(U,A)
+del(U)
+repl(U,U)
+del(U)
+repl(U,M)
+del(U)
GRAU ↓ ε 4
+ins(R)
GRAU ↓ R 3
+ins(A)
GRAU ↓ RA 2
+ins(U)
GRAU ↓ RAU 1
+ins(M)
GRAU ↓ RAUM 2

UNI FREIBURG

How to get the sequence of operations?

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- We save at each recursion the most efficient previous entry (the highlighted arrows in our image)

Edit distance

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- There can be more than one arrows to the three previous entries

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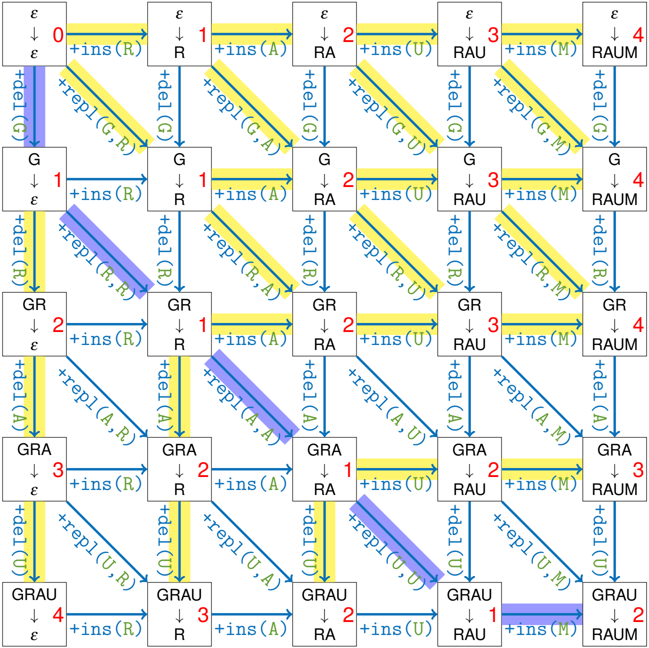
- There can be more than one arrows to the three previous entries
- If we follow the highlighted path from (n, m) to $(1, 1)$ we get the optimum operations to transform x into y
  - If we can follow more than one path there exist more than one ideal sequence



ε ↓ ε 0
ε ↓ R 1
ε ↓ RA 2
ε ↓ RAU 3
ε ↓ RAUM 4
G ↓ ε 1
G ↓ R 1
G ↓ RA 2
G ↓ RAU 3
G ↓ RAUM 4
GR ↓ ε 2
GR ↓ R 1
GR ↓ RA 2
GR ↓ RAU 3
GR ↓ RAUM 4
GRA ↓ ε 3
GRA ↓ R 2
GRA ↓ RA 1
GRA ↓ RAU 2
GRA ↓ RAUM 3
GRAU ↓ ε 4
GRAU ↓ R 3
GRAU ↓ RA 2
GRAU ↓ RAU 1
GRAU ↓ RAUM 2
+ins(R)
+ins(A)
+ins(U)
+ins(M)
+del(G)
+del(R)
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+del(U)
+repl(G,R)
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+repl(G,U)
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+repl(R,U)
+repl(R,M)
+repl(A,R)
+repl(A,A)
+repl(A,U)
+repl(A,M)
+repl(U,R)
+repl(U,A)
+repl(U,U)
+repl(U,M)

Edit distance

General principle:

Edit distance

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- Recursive computation of …
  - … the same reoccuring partial problems
  - … a limited number of partial problems

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Edit distance

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- Recursive computation of ...
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Edit distance

General principle:

- Recursive computation of ...
  - ... the same reoccuring partial problems
  - ... a limited number of partial problems
- Computation of the solutions for all partial problems
- In a order that unsolved partial problems consist of already solved partial problems
- The „path“ to our solution normally gets computed while searching the best solution
- Dijkstra algorithm is basically dynamic programming!

Additional applications:

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- *Edit distance*: global alignment with $O(n^2)$ space and time consumption

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  - In evolution larger pieces are more likely

Edit distance

Additional applications (I)

Additional applications:

- *Edit distance*: global alignment with $O(n^2)$ space and time consumption
- But: Model for deletition unrealistic
  - In evolution larger pieces are more likely
  - `delete` operation: first gap expensive (e.g. 2), remaining are cheaper (e.g. 0.5)

_	_	_	B	L	O	E	D
S	A	U	B	L	O	E	D

Additional applications:

- *Edit distance*: global alignment with $O(n^2)$ space and time consumption
- But: Model for deletition unrealistic
  - In evolution larger pieces are more likely
  - `delete` operation: first gap expensive (e.g. 2), remaining are cheaper (e.g. 0.5)

$$
\begin{array}{cccccccc}
\_ & \_ & \_ & B & L & O & E & D \\
S & A & U & B & L & O & E & D
\end{array}
$$

  - Solution in $O(n^3)$ time or $O(n^2)$ affine

$O(n^2)$ space consumption might be problematic:

Hirschberg algorithm:

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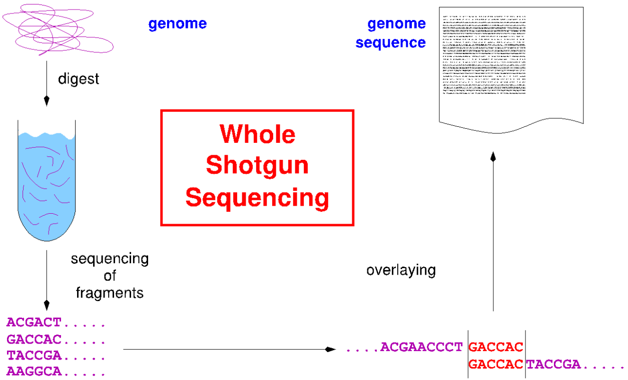
Hirschberg algorithm:

- Divide-and-conquer approach

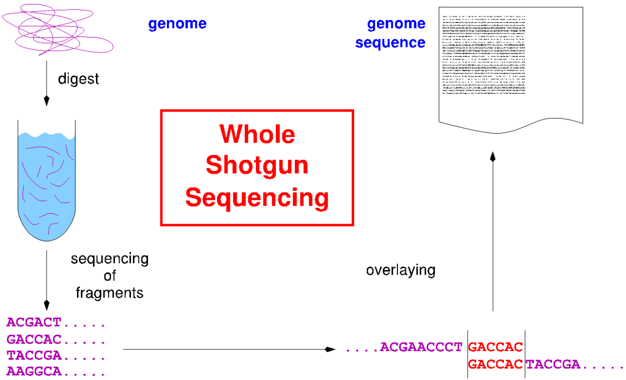
$O(n^2)$ space consumption might be problematic:

Hirschberg algorithm:

- Divide-and-conquer approach
- $O(n)$ space and $O(n^2)$ time consumption



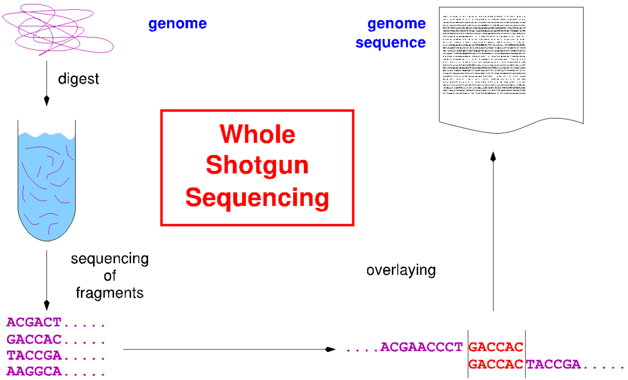
genome
digest
Whole Shotgun Sequencing
genome sequence
sequencing of fragments
overlaying
ACGACT.....
GACCAC.....
TACCGA.....
AAGGCA.....
....ACGAACCCT GACCAC
GACCAC TACCGA.....



- Sequencing: $O(n^2)$ is too much

Edit distance

Additional applications (III)



- Sequencing: $O(n^2)$ is too much
- Index: suffixtree, suffixarray, burrow-wheeler-transform

Further Literature

- **General**

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.
Introduction to Algorithms.
MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.
Algorithms and data structures, 2008.
https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf.

Further Literature

- **Dynamic programming**

  [Wik] Dynamic programming
  https://en.wikipedia.org/wiki/Dynamic_programming

- **Edit distance**

  [Wik] Levenshtein distance
  https://en.wikipedia.org/wiki/Levenshtein_distance