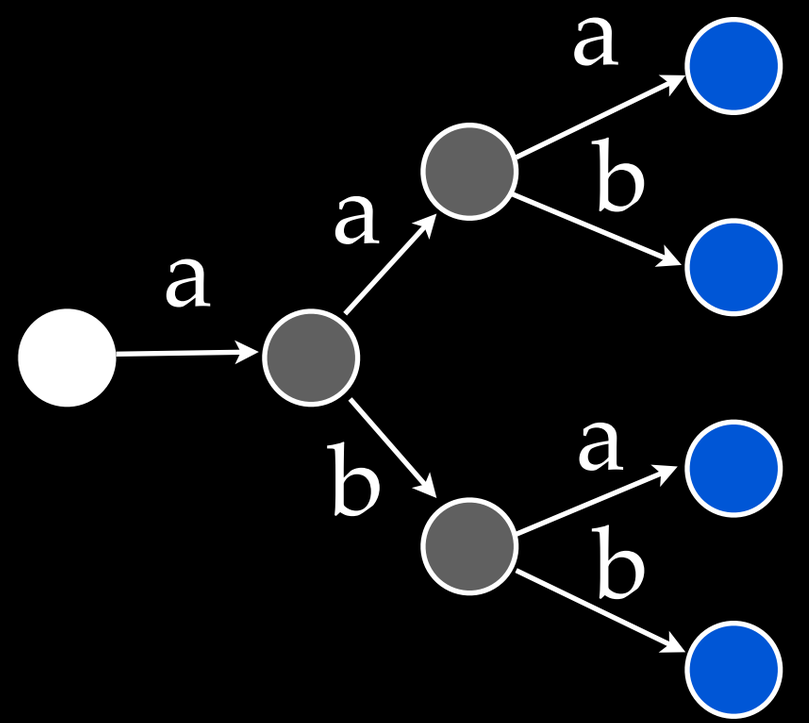
Syntax-Based Translation with Weighted Automata

Review

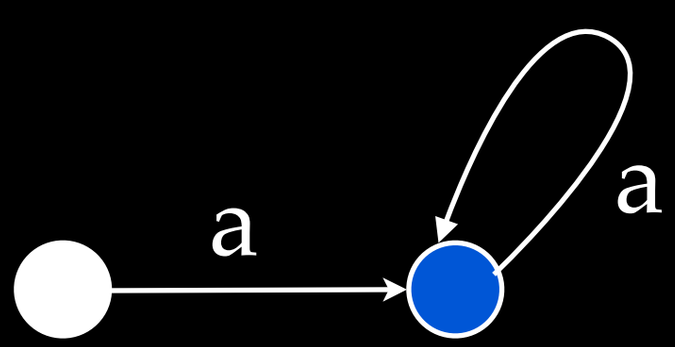
- We need efficient algorithms and data structures to:
  - Encode all of the strings in the language.
  - Assign probabilities to all of those strings.
    - Via products such as $p(e)p(f \mid e)$.
  - Find the string with the highest probability.
  - Compute expectations over substrings.
  - Compute mappings between strings.

Regular Languages

$$\mathcal{L}_1 = \left\{ \begin{array}{l} \text{a a a} \\ \text{a b a} \\ \text{a a b} \\ \text{a b b} \end{array} \right\}$$

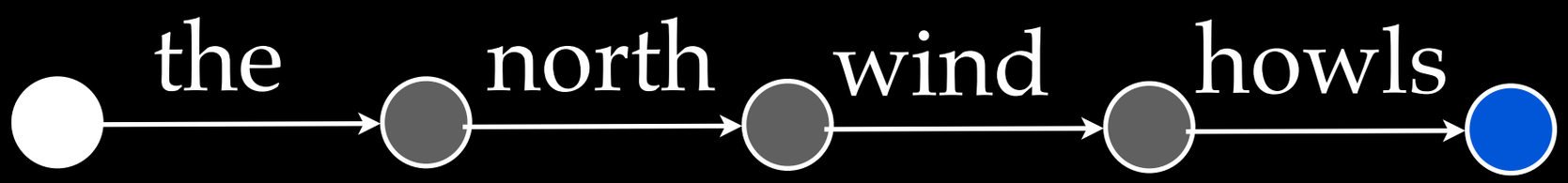


$$\mathcal{L}_2 = a^* = \{a, aa, aaa, ...\}$$



$\mathcal{L}_3$ = { "the north wind howls" }

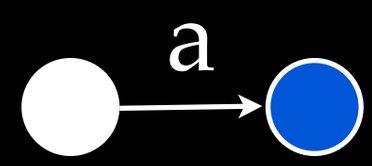
finite-state automata



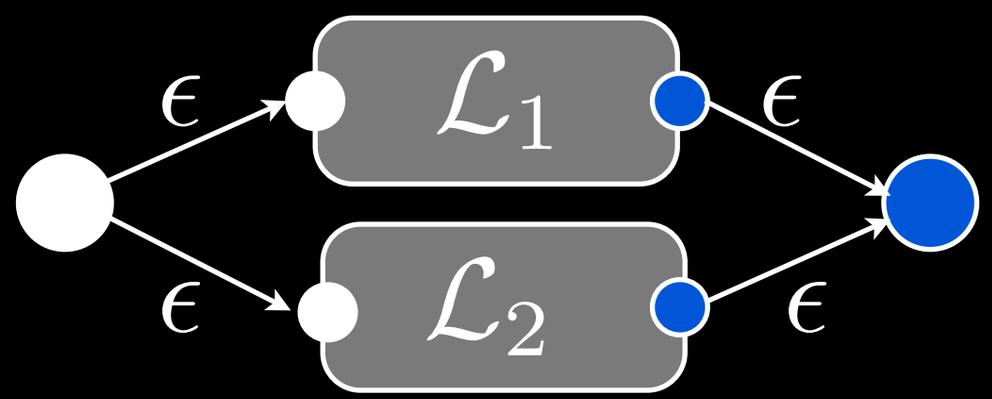
Regular Languages

$\{\epsilon\}$ is regular

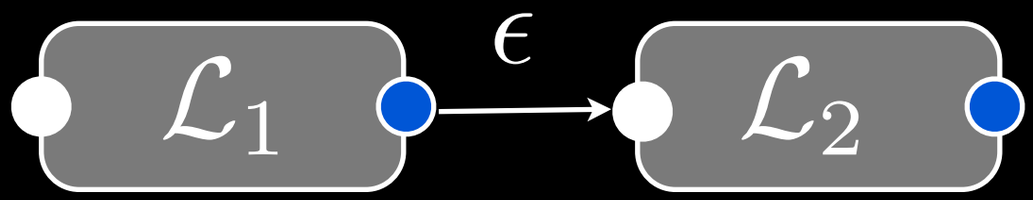
$\{a\}$ is regular



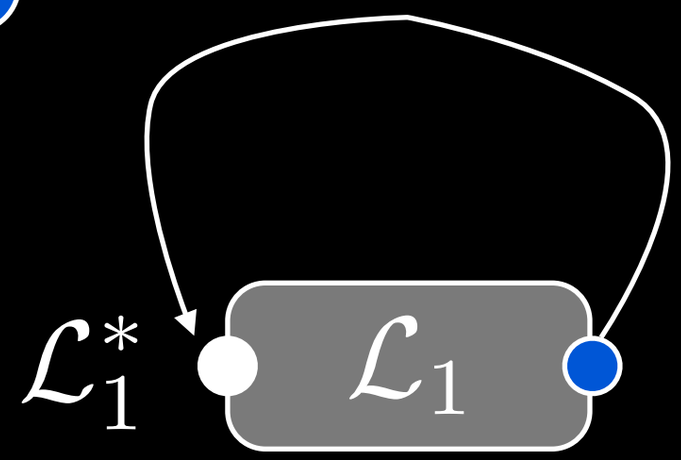
$\mathcal{L}_1 \cup \mathcal{L}_2$ is regular if $\mathcal{L}_1$ and $\mathcal{L}_2$ are regular



$\mathcal{L}_1 \cdot \mathcal{L}_2$



$\mathcal{L}_1^*$



Regular Languages

Not all languages are regular!

$$\mathcal{L}_4 = \{ab, aabb, aaabbb, ...\} = \forall_{n \in [1,\text{inf})} a^n b^n$$

Over the last two weeks we saw *context-free* languages.

Context-Free Grammar

Context-Free Grammar

S → NP VP
NP → watashi wa
NP → hako wo
VP → NP V
V → akemasu

Context-Free Grammar

S

S → NP VP

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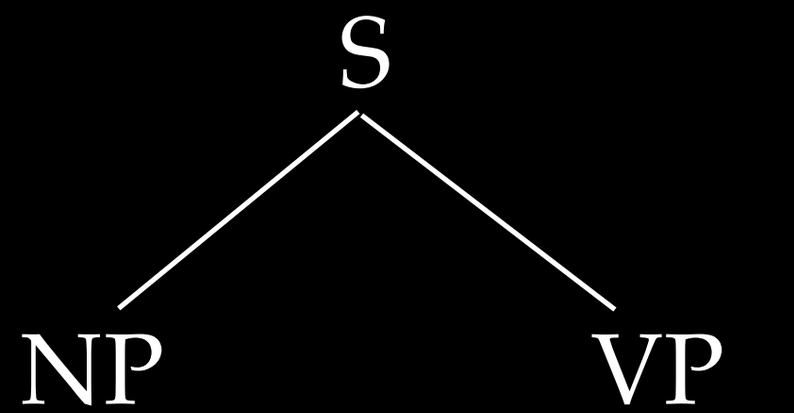

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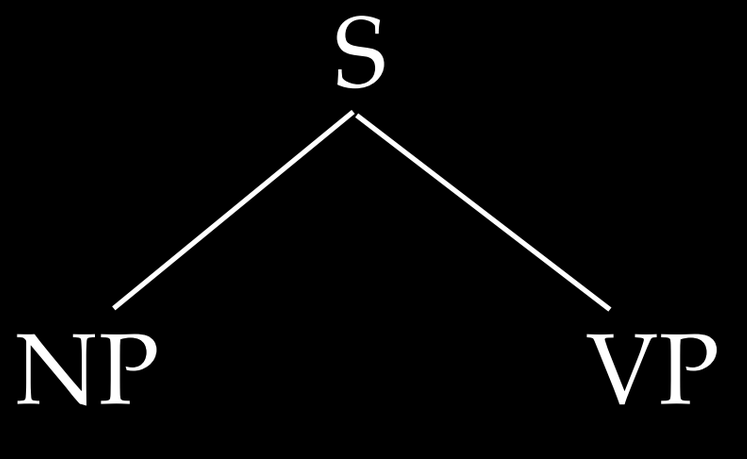

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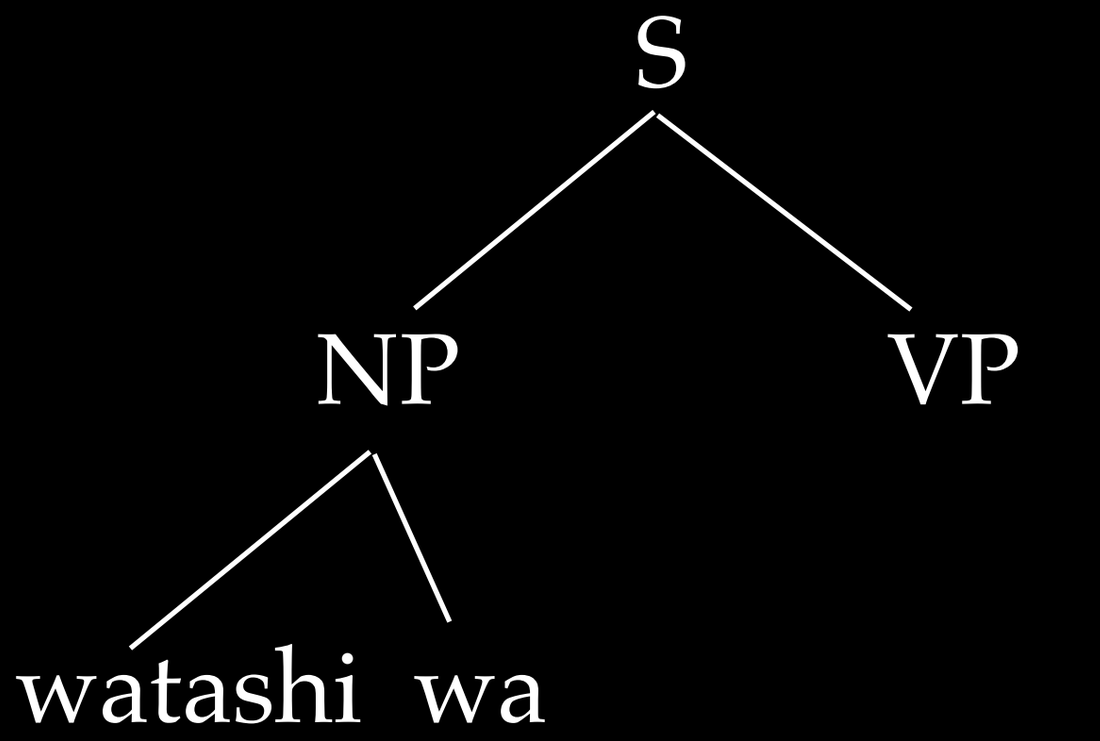

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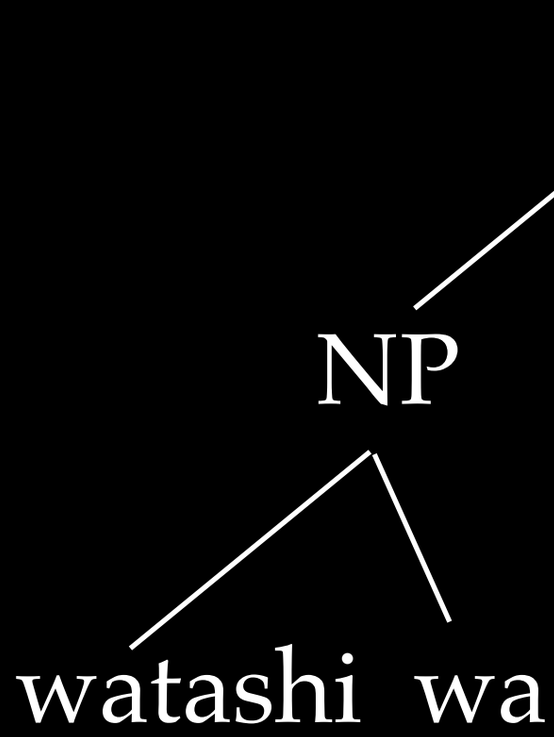

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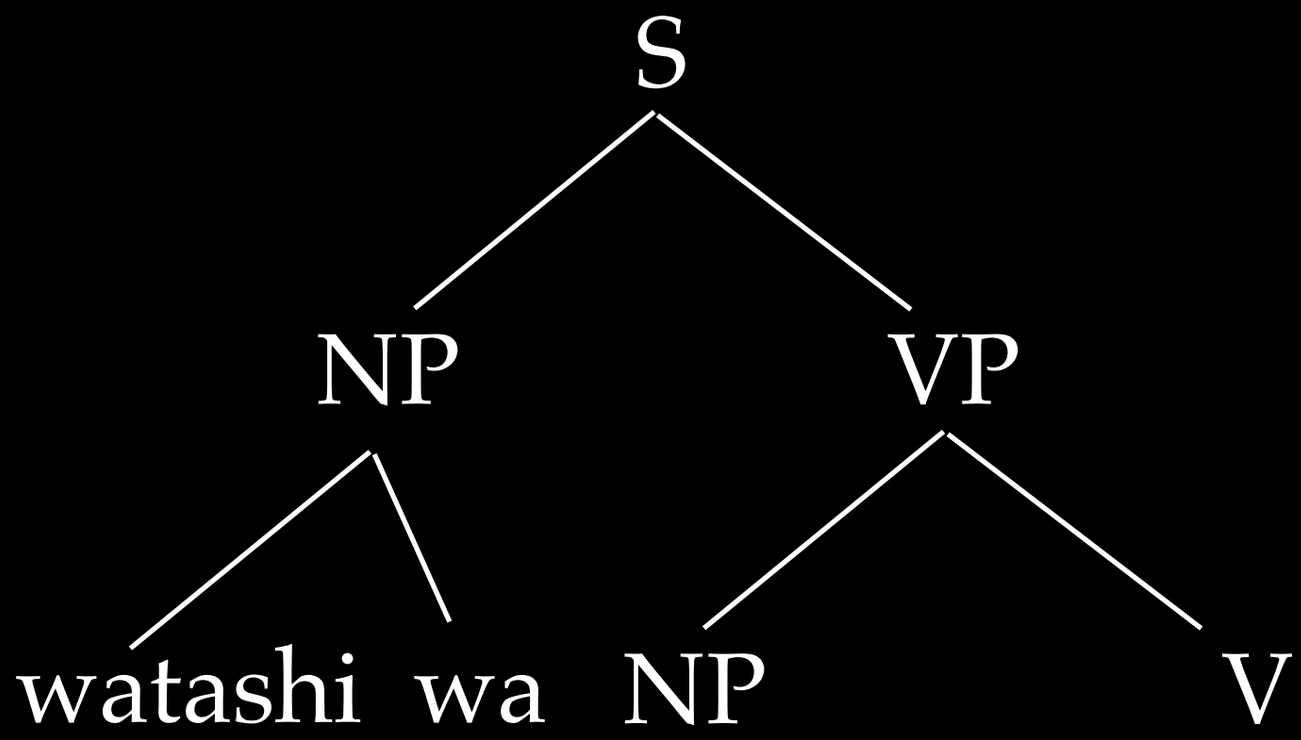

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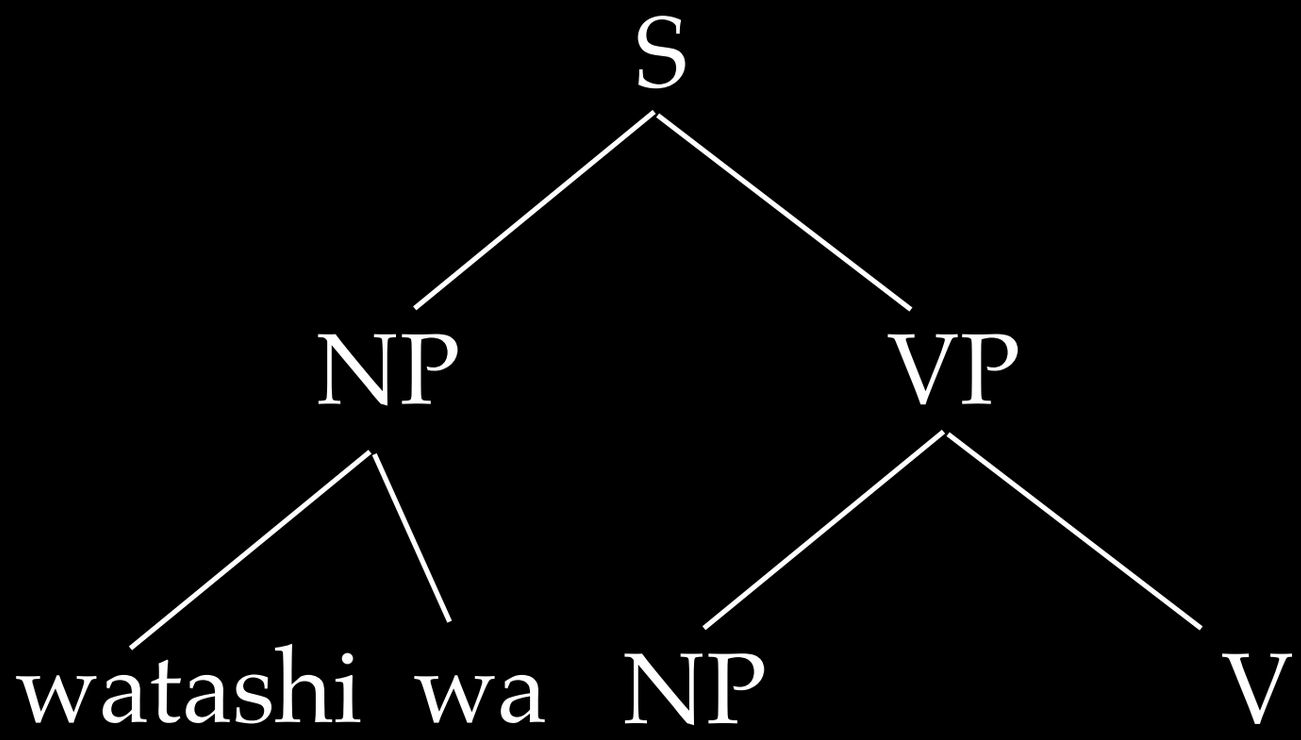

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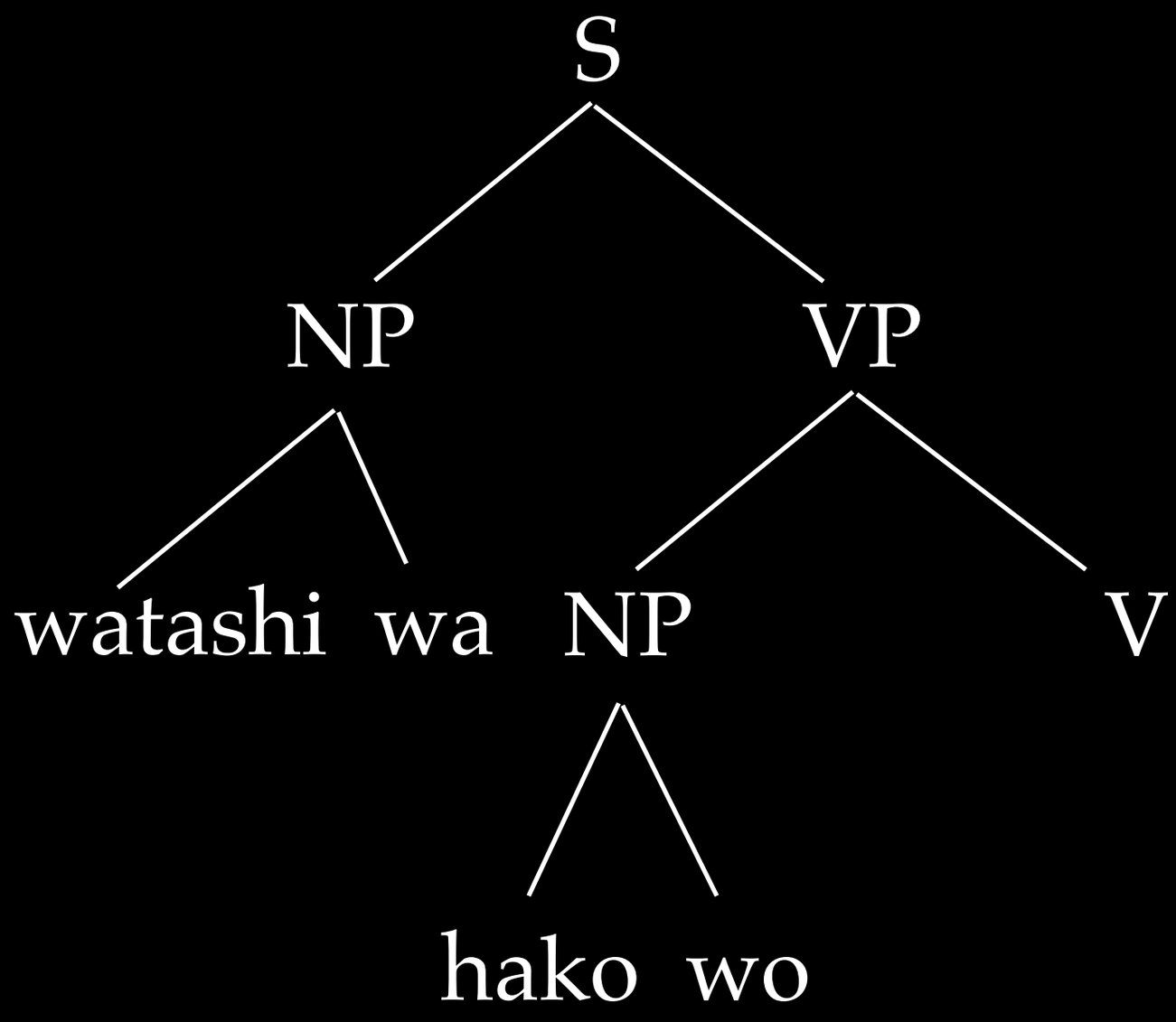

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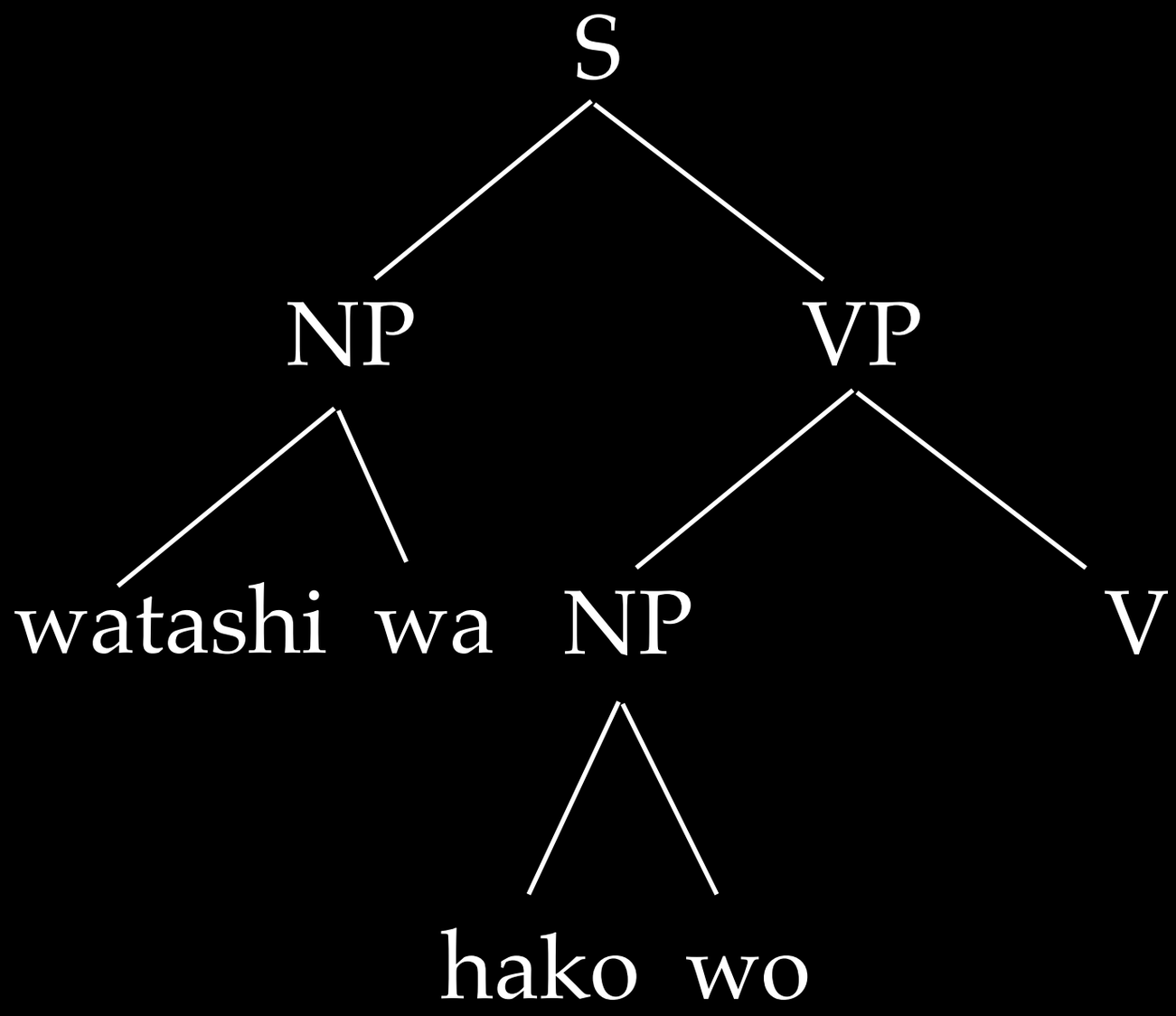

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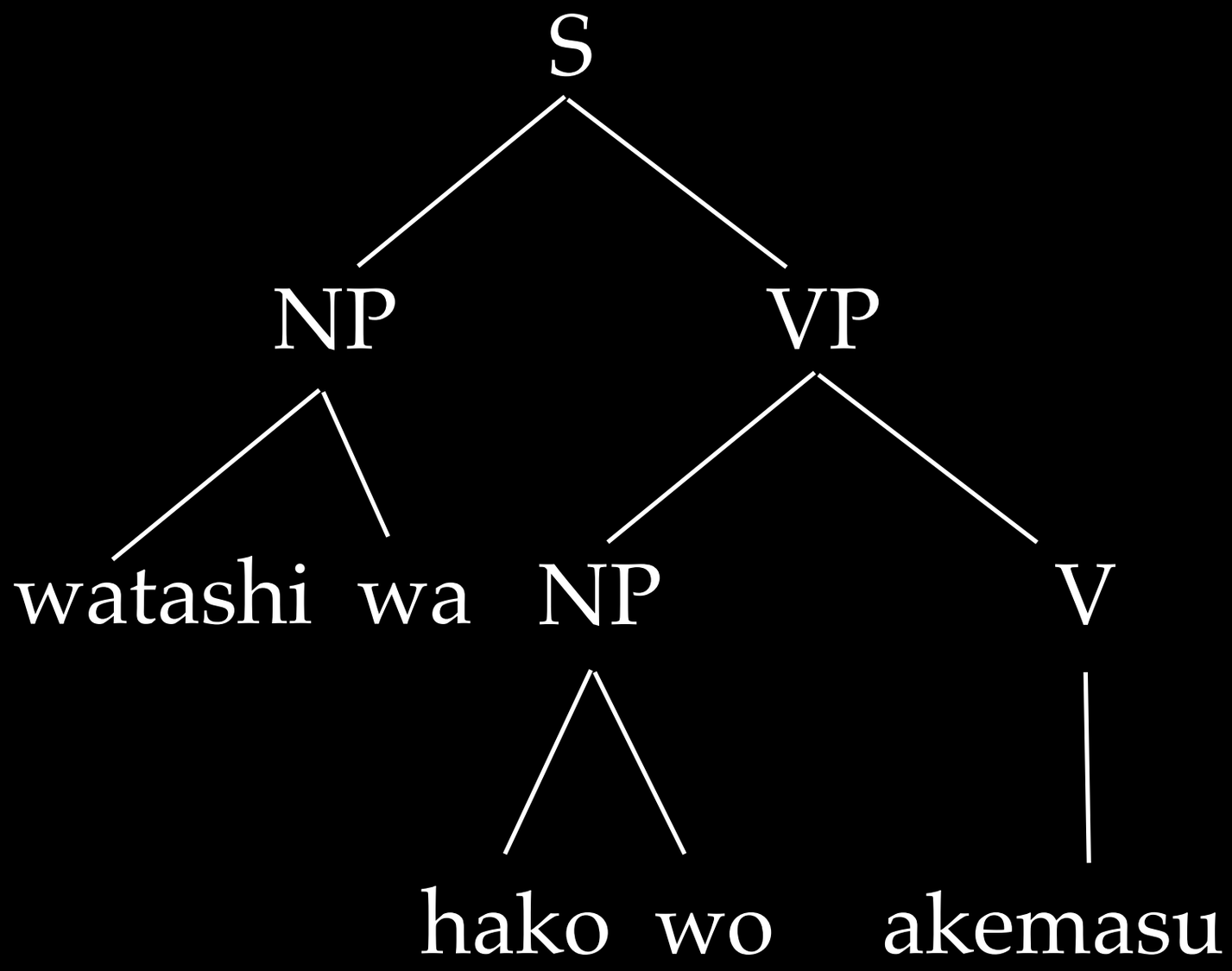

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$NP \rightarrow$ hako wo

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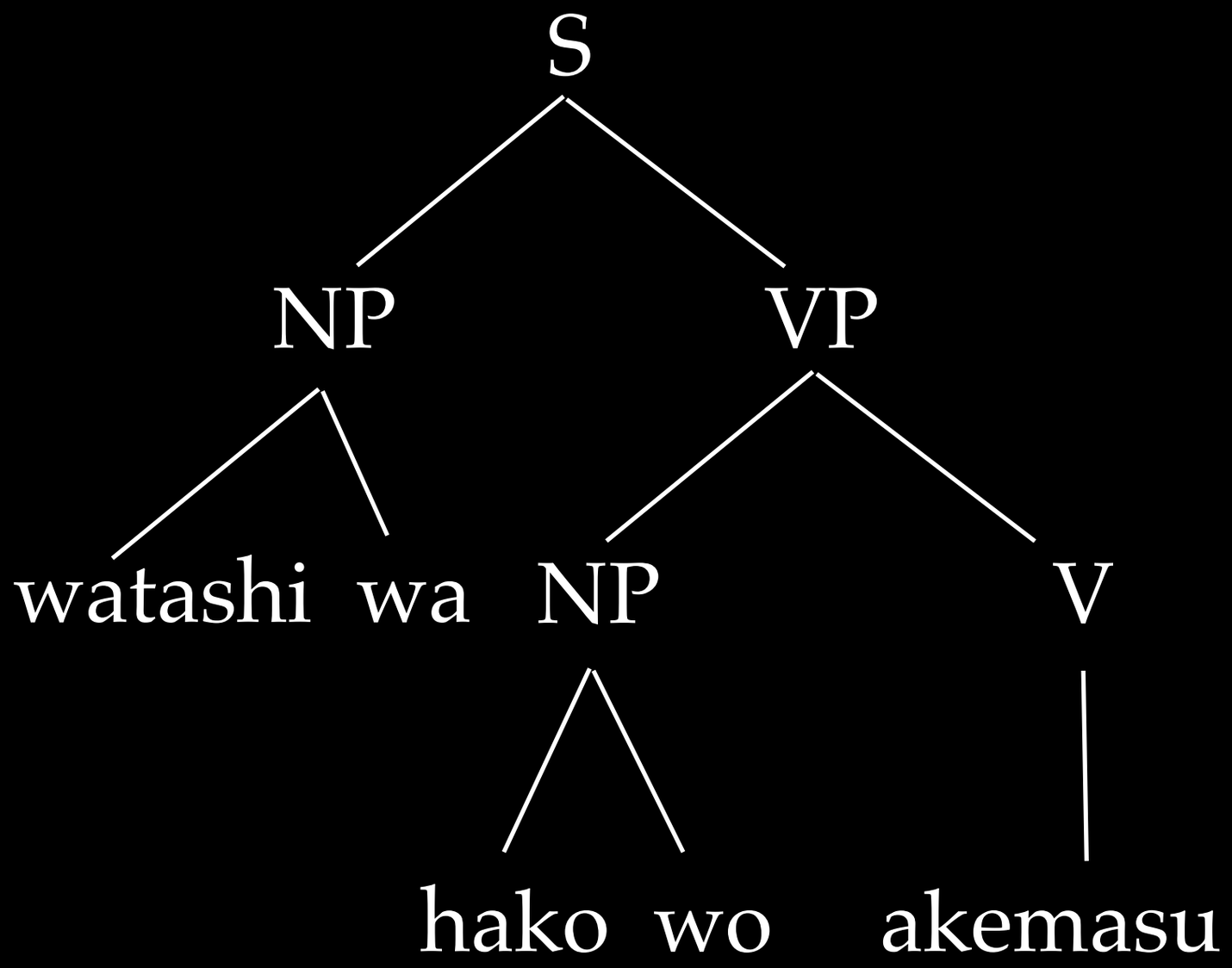

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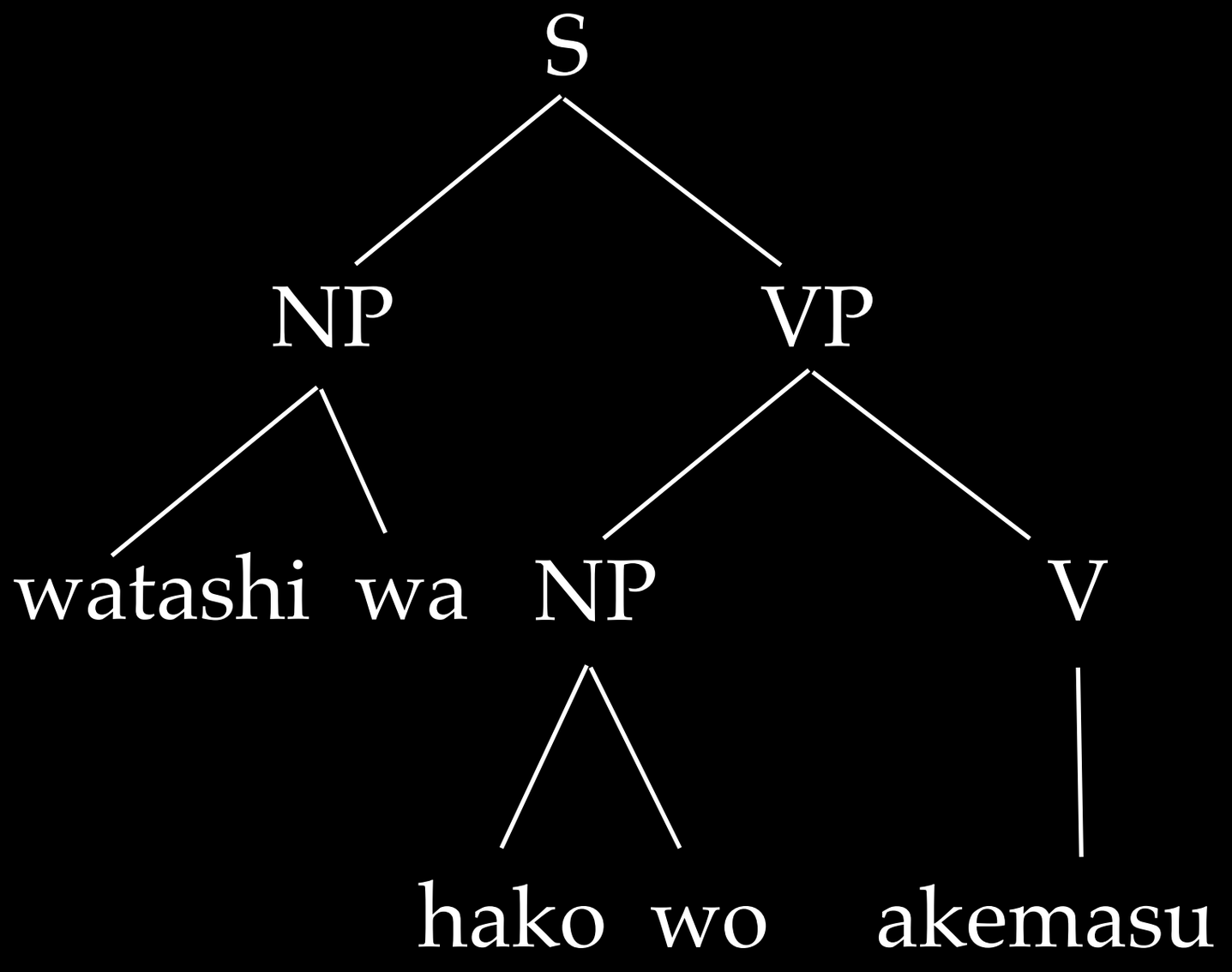


watashi wa hako wo akemasu

Context-Free Grammar

$S \rightarrow NP\ VP$
$NP \rightarrow$ watashi wa
$NP \rightarrow$ hako wo
$VP \rightarrow NP\ V$
$V \rightarrow$ akemasu

Note: this particular grammar is finite, hence regular.

$$\left\{\begin{array}{c}\text{watashi wa watashi wa akemasu}\\ \text{watashi wa hako wo akemasu}\\ \text{hako wo hako wo akemasu}\\ \text{hako wo watashi wa akemasu}\end{array}\right\}$$

Context-Free Grammar

$S \rightarrow A\ B$

$S \rightarrow A\ S\ B$

$A \rightarrow a$

$B \rightarrow b$

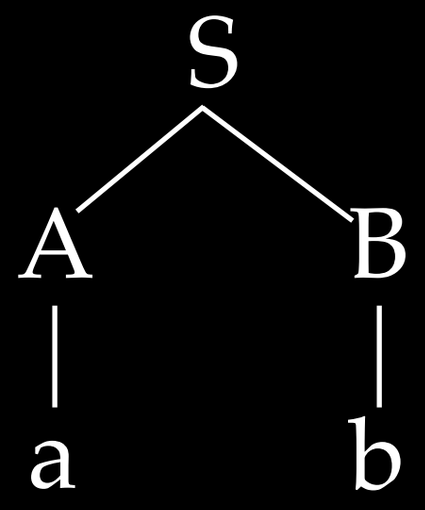
Context-Free Grammar

$S \rightarrow A\,B$

$S \rightarrow A\,S\,B$

$A \rightarrow a$

$B \rightarrow b$



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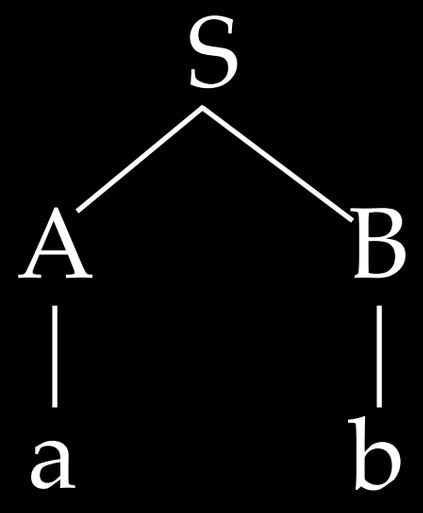

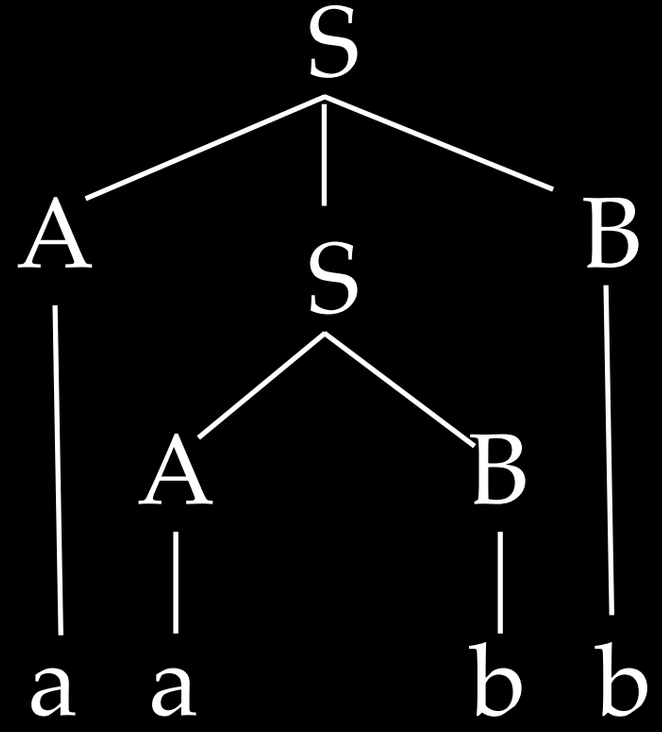

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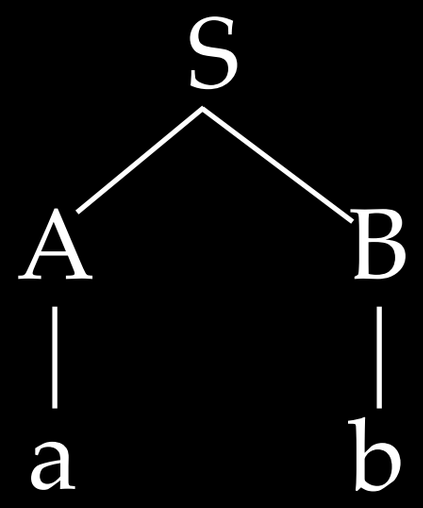

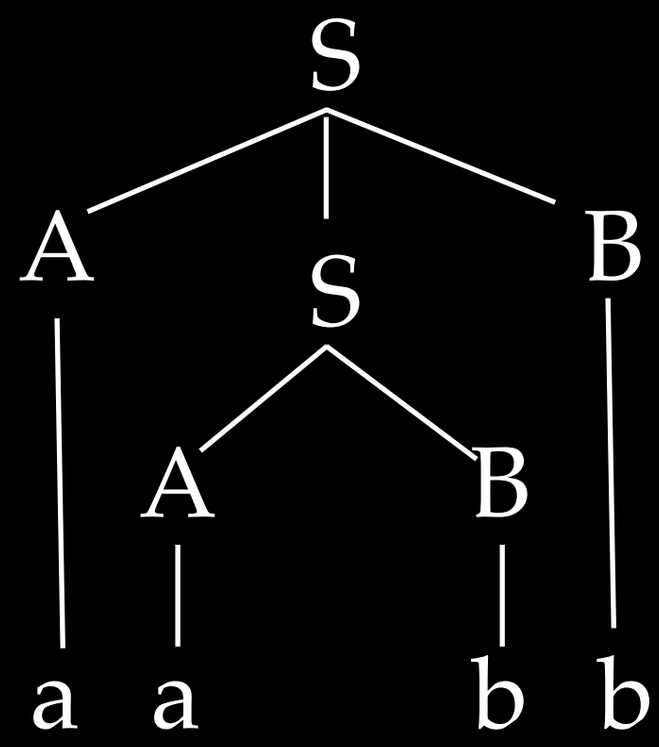

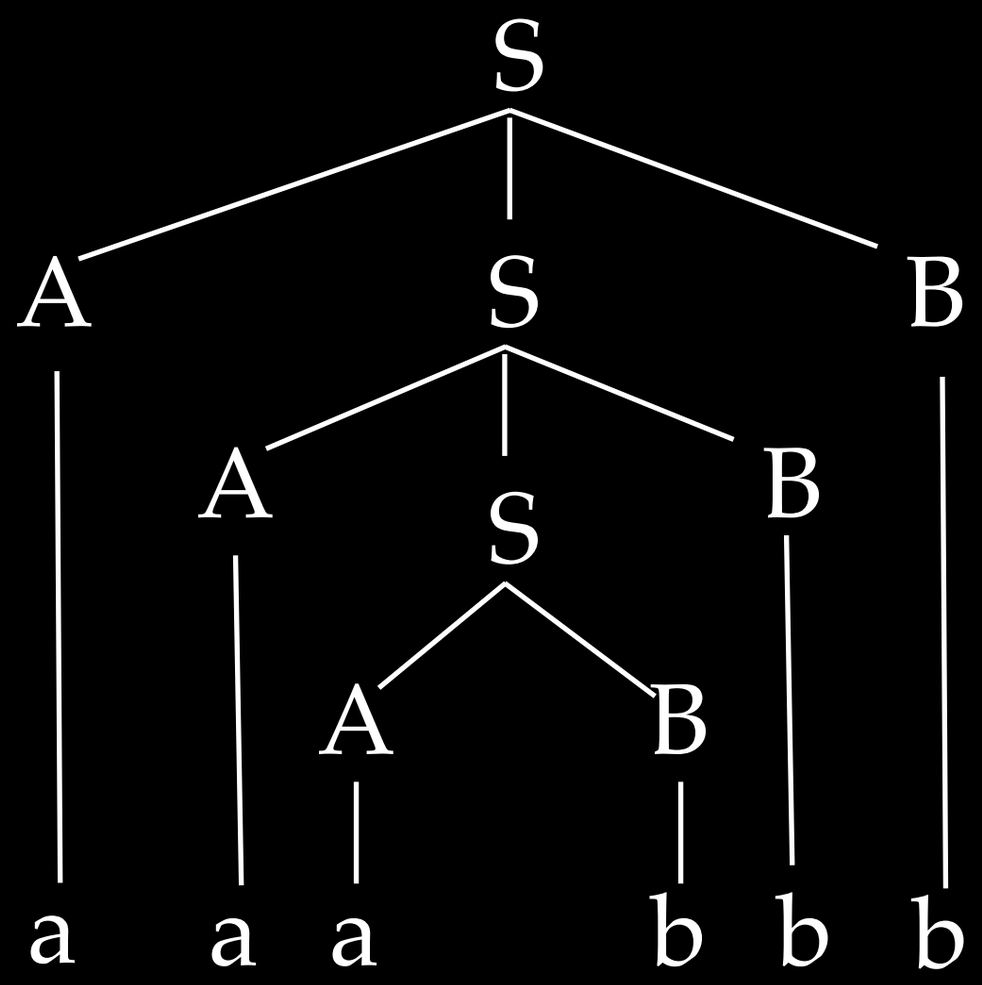

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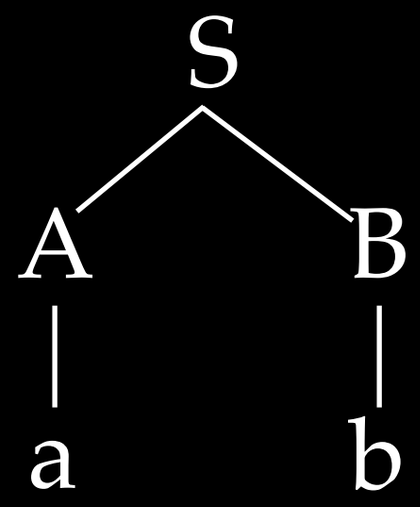

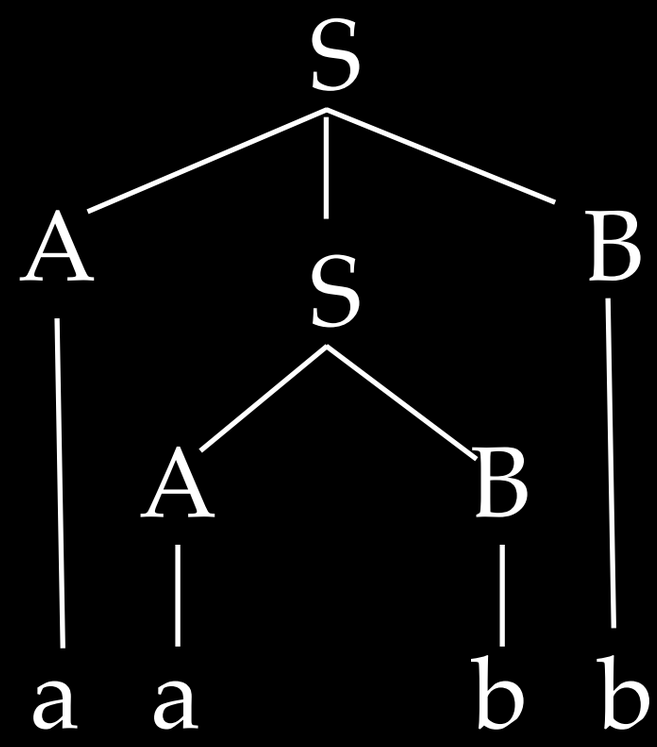

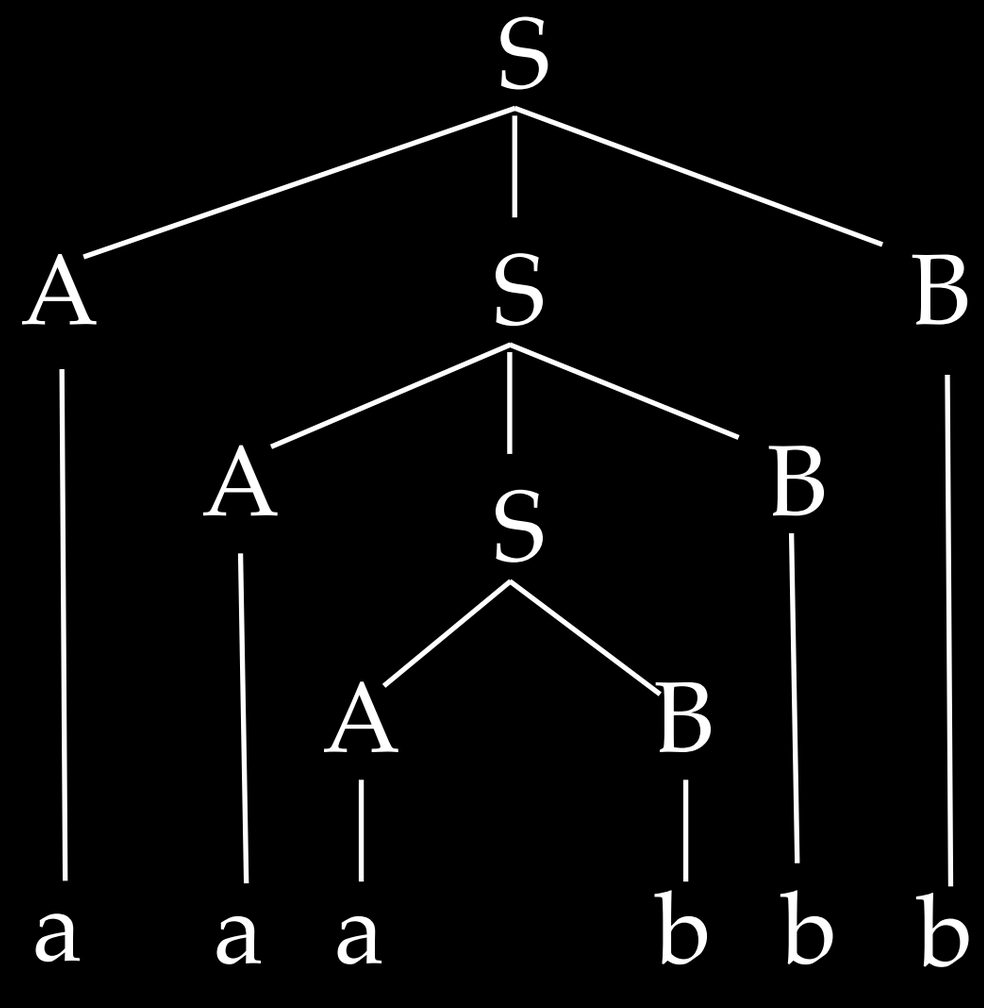

$$\mathcal{L}_4 = \{ab, aabb, aaabbb, ...\} = \forall_{n \in [1,\text{inf})} a^n b^n$$

Context-Free vs. Regular

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- Regular languages $\subset$ Context-free languages

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- Composition of languages:

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  - Regular $\cap$ Regular = Regular

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$$A \rightarrow BC \in \mathcal{G}_{CFL}$$

Context-Free vs. Regular

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  - Regular $\cap$ Regular = Regular
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$A \rightarrow BC \in \mathcal{G}_{CFL}$ $\qquad$ $s, r, t \in states(\mathcal{G}_{RL})$

Context-Free vs. Regular

- Regular languages $\subset$ Context-free languages
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$$A \rightarrow BC \in \mathcal{G}_{CFL} \qquad s, r, t \in states(\mathcal{G}_{RL})$$
$$ {}_sA_t \rightarrow {}_sB_{rr}C_t \in \mathcal{G}_{CFL} \cap \mathcal{G}_{RL}$$

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Bar-Hillel 1964

Context-Free vs. Regular

- Regular languages $\subset$ Context-free languages
- Composition of languages:
  - Regular $\cap$ Regular = Regular
  - Regular $\cap$ Context-free = Context-free
  - Context-free $\cap$ Context-free = Undecidable

$$A \rightarrow BC \in \mathcal{G}_{CFL} \qquad s, r, t \in states(\mathcal{G}_{RL})$$

$$_sA_t \rightarrow {}_sB_{rr}C_t \in \mathcal{G}_{CFL} \cap \mathcal{G}_{RL}$$

Bar-Hillel 1964

Synchronous Context-Free Grammar

S → NP VP

NP → watashi wa

NP → hako wo

VP → NP V

V → akemasu

Synchronous Context-Free Grammar

S → NP VP	S → NP VP
NP → watashi wa	NP → I
NP → hako wo	NP → the box
VP → NP V	VP → V NP
V → akemasu	V → open

Synchronous Context-Free Grammar

$S \rightarrow NP_1\ VP_2\ /\ NP_1\ VP_2$

NP → watashi wa / I

NP → hako wo / the box

$VP \rightarrow NP_1\ V_2\ /\ V_1\ NP_2$

V → akemasu / open

Synchronous Context-Free Grammar

$S \rightarrow NP_1\ VP_2\ /\ NP_1\ VP_2$

$NP \rightarrow$ watashi wa / I

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$V \rightarrow$ akemasu / open

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S S

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Synchronous Context-Free Grammar

S ..... S

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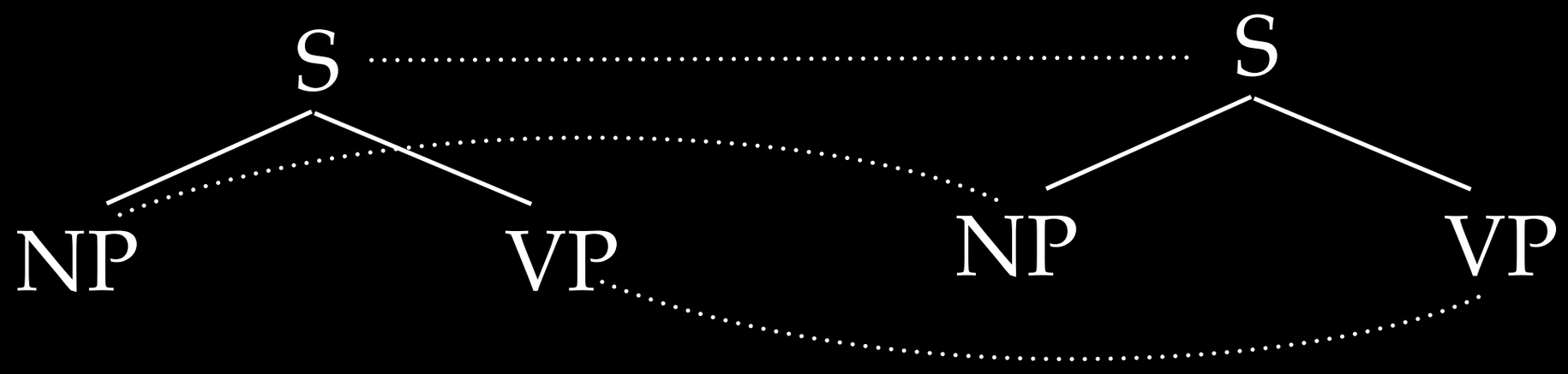

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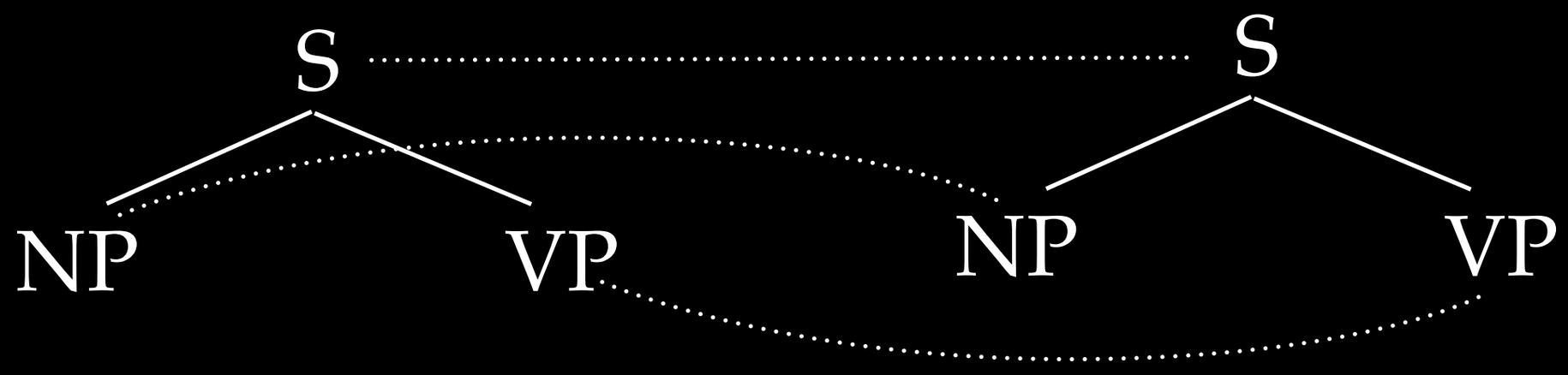

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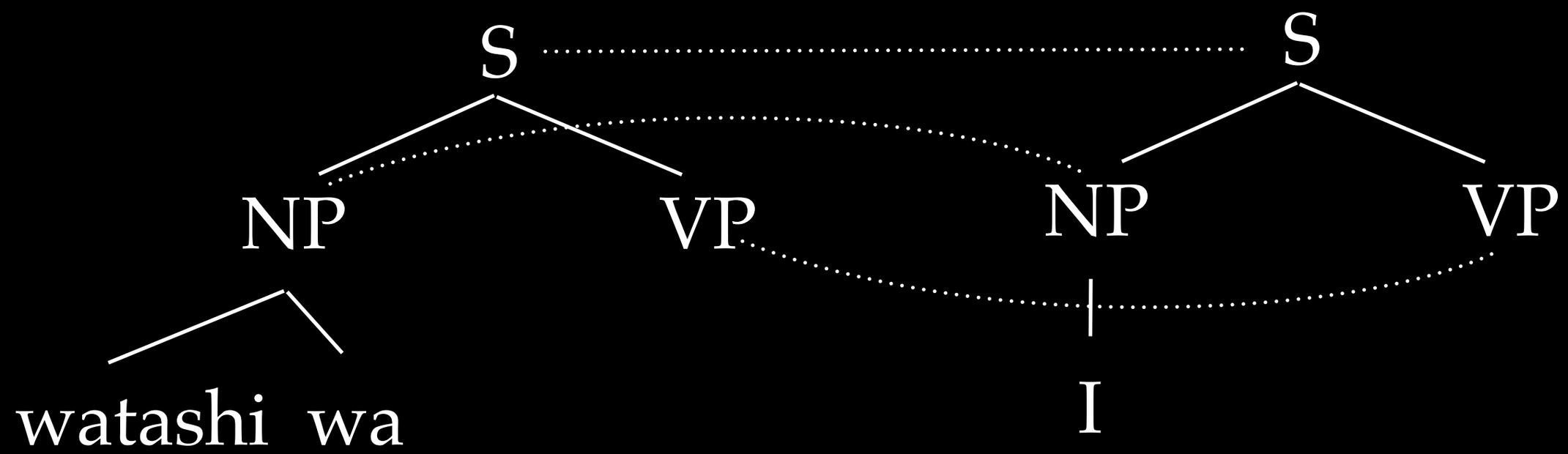

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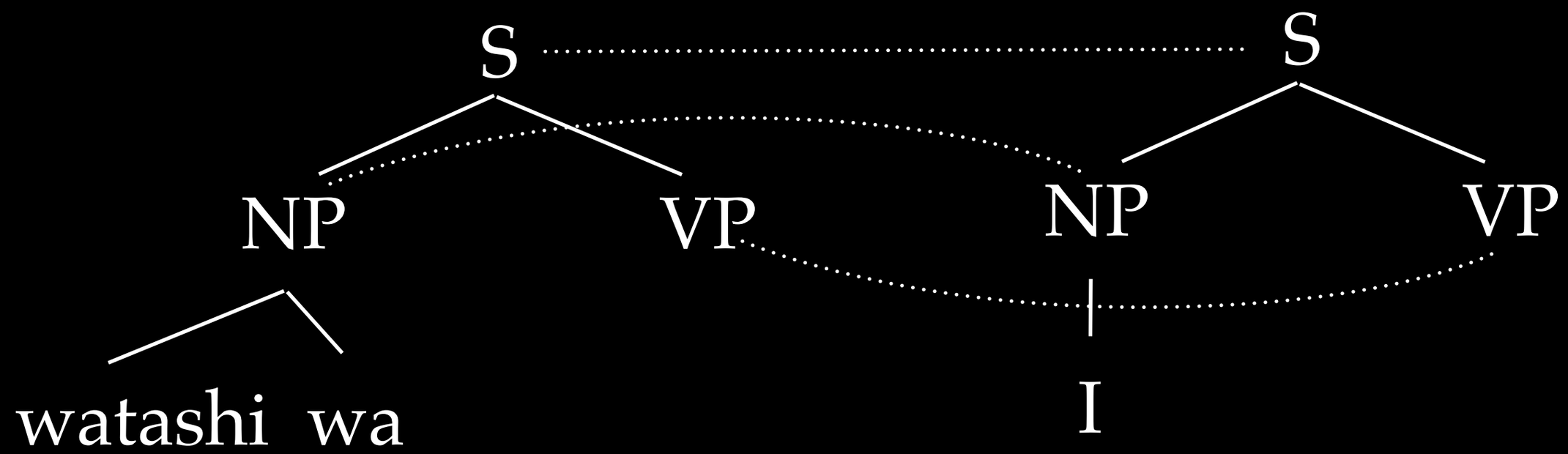

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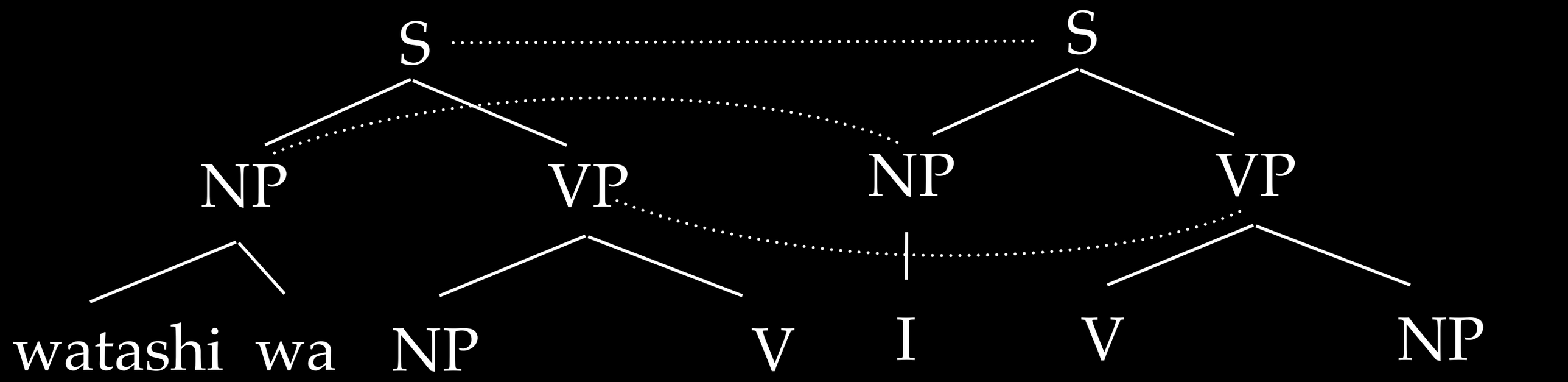

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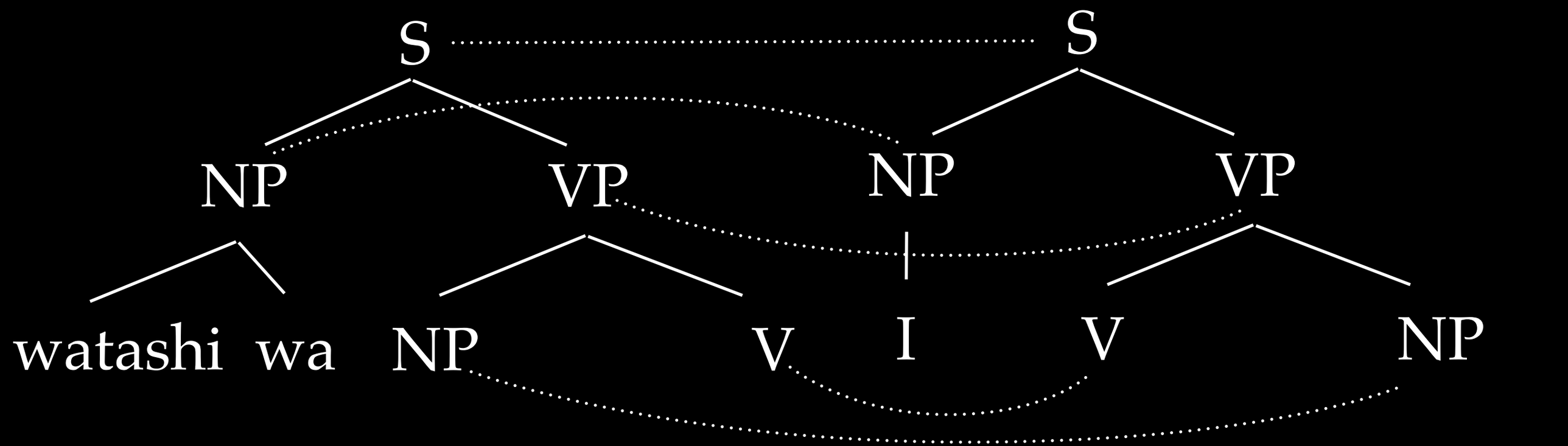

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$VP \rightarrow NP_1\ V_2\ /\ V_1\ NP_2$

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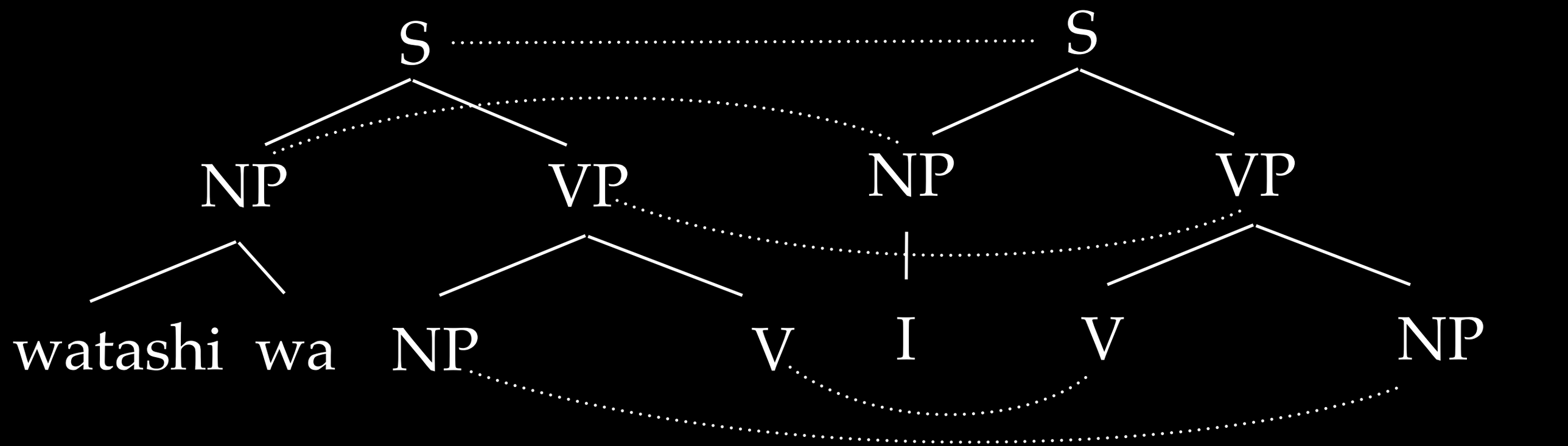

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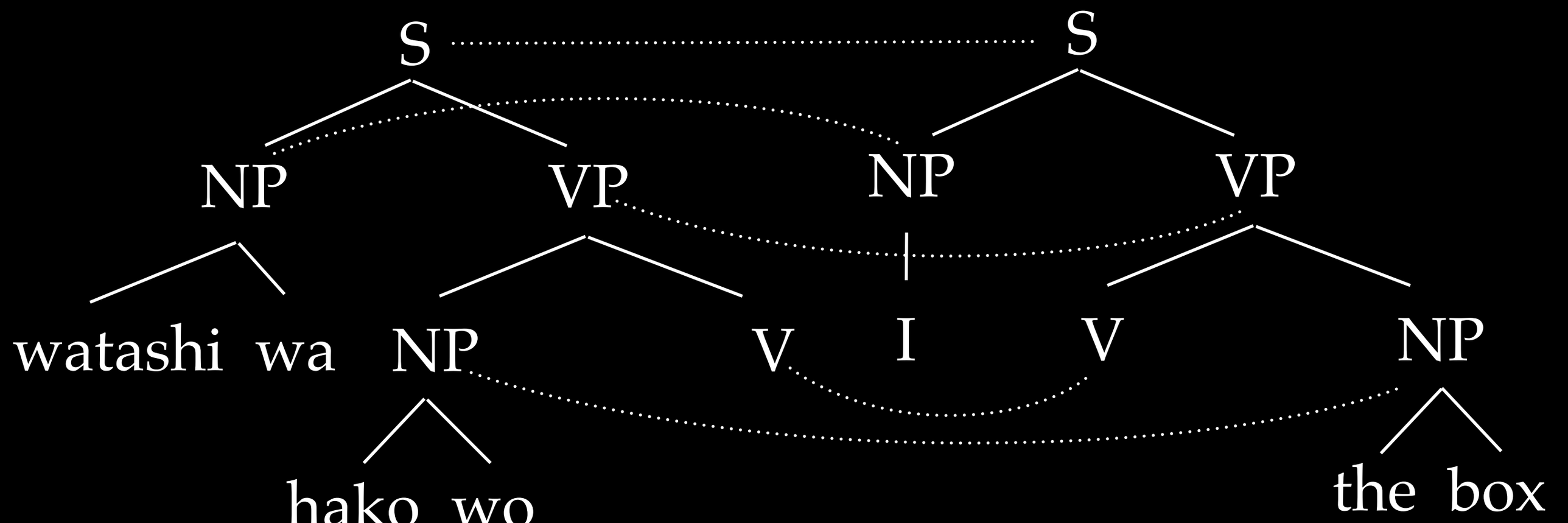

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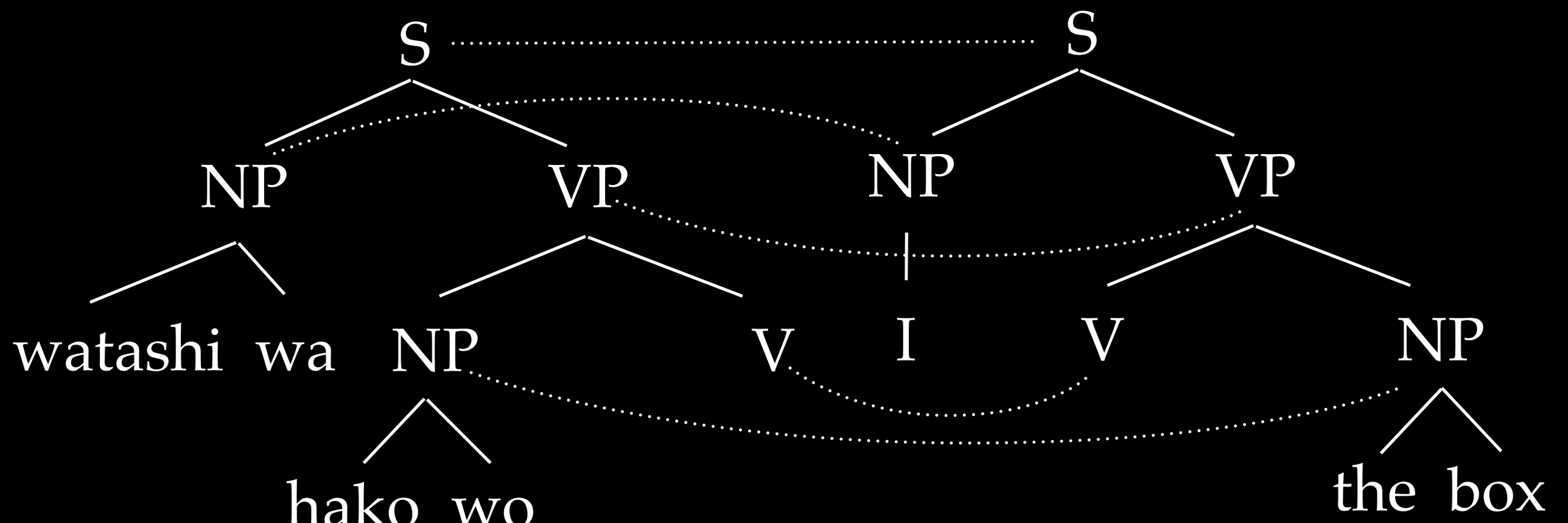

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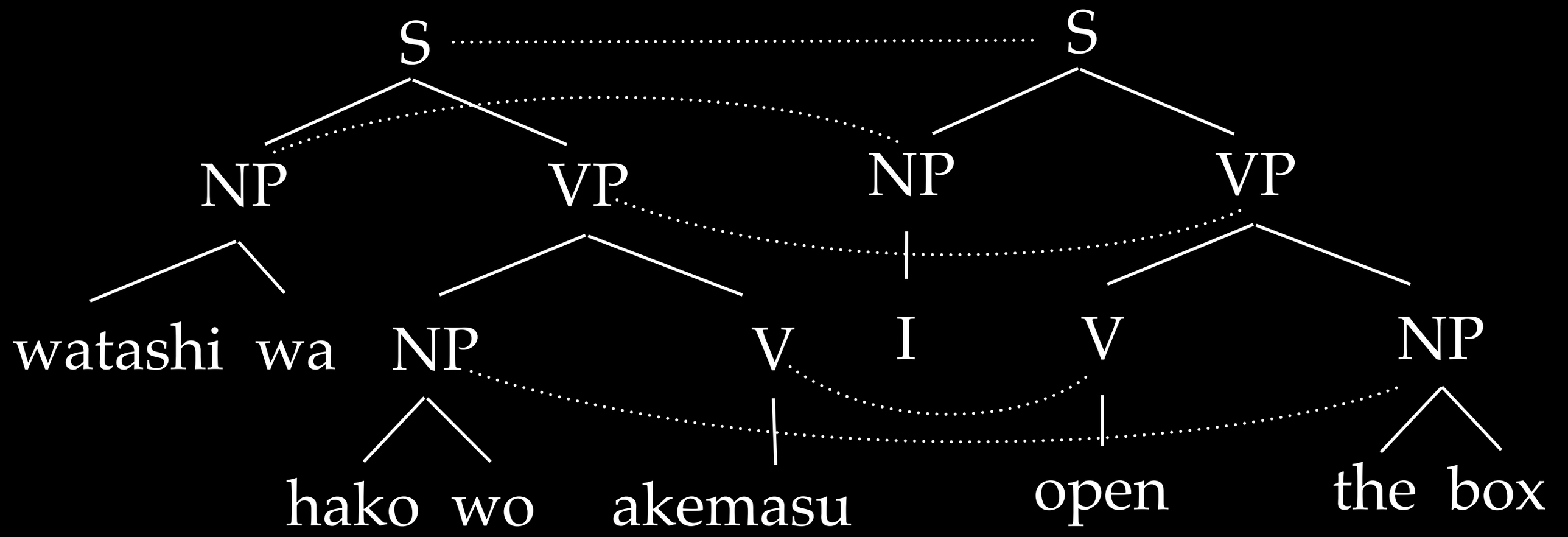
NP → watashi wa / I

NP → hako wo / the box

$VP \rightarrow NP_1\ V_2\ /\ V_1\ NP_2$

V → akemasu / open

Synchronous Context-Free Grammar



$S \rightarrow NP_1\ VP_2\ /\ NP_1\ VP_2$

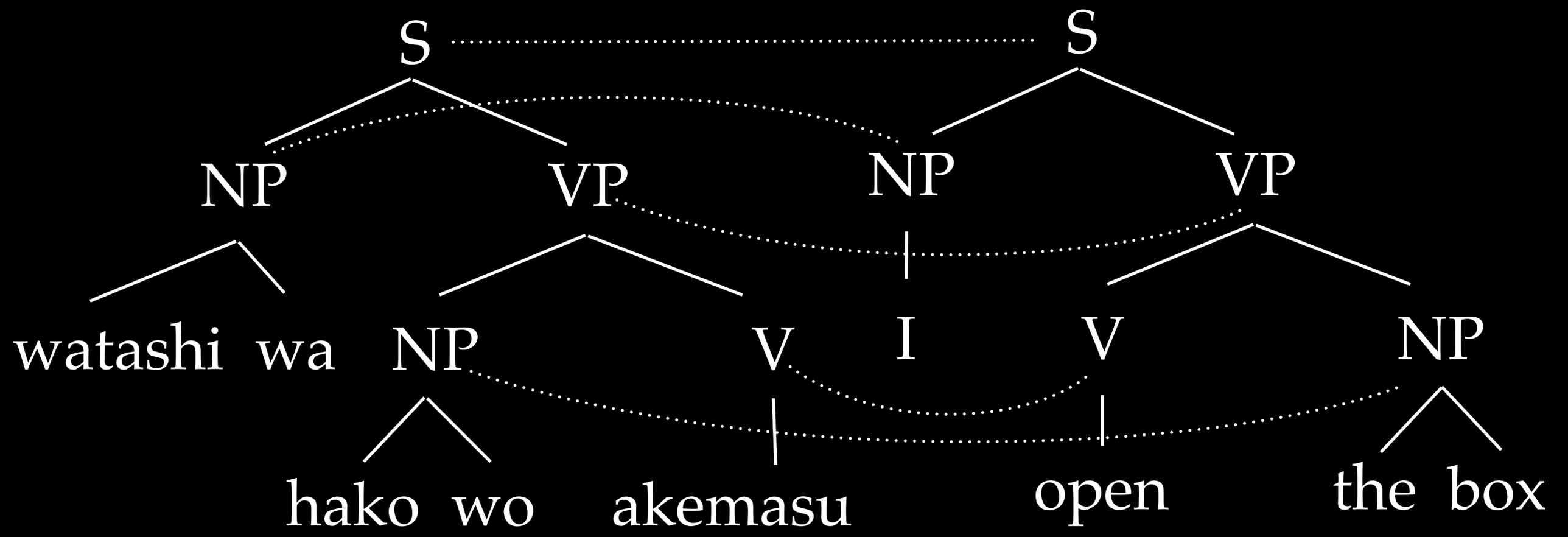
NP → watashi wa / I

NP → hako wo / the box

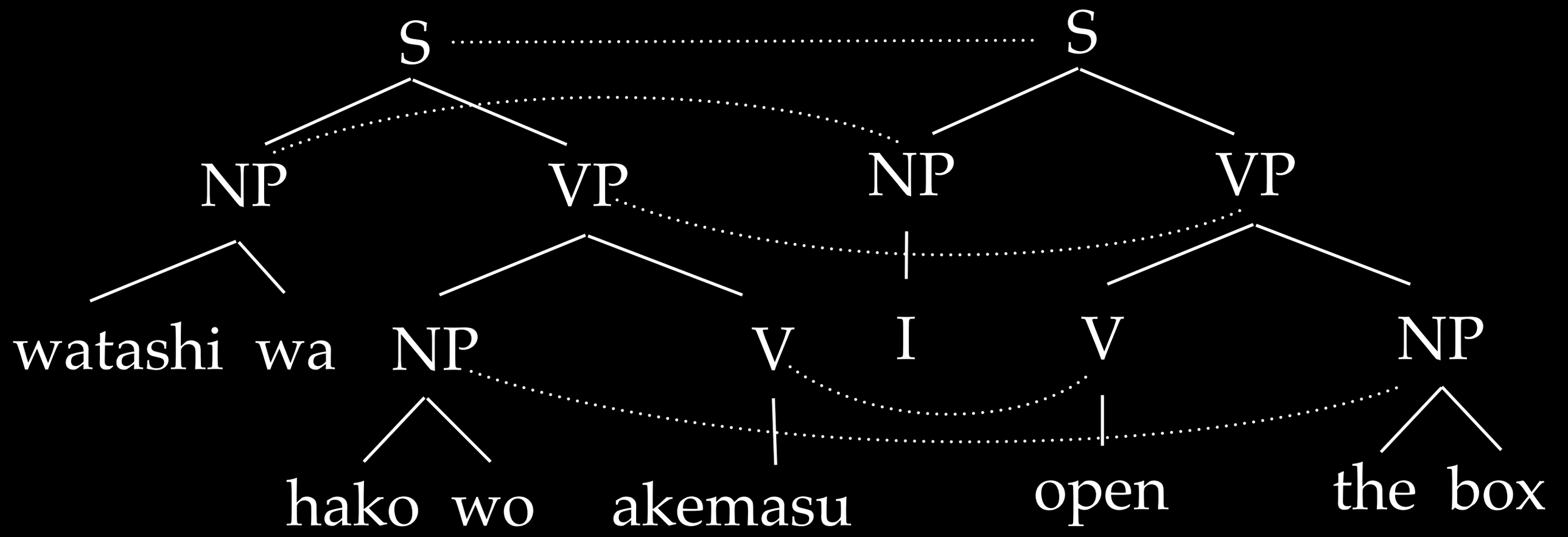
$VP \rightarrow NP_1\ V_2\ /\ V_1\ NP_2$

V → akemasu / open

Synchronous Context-Free Grammar

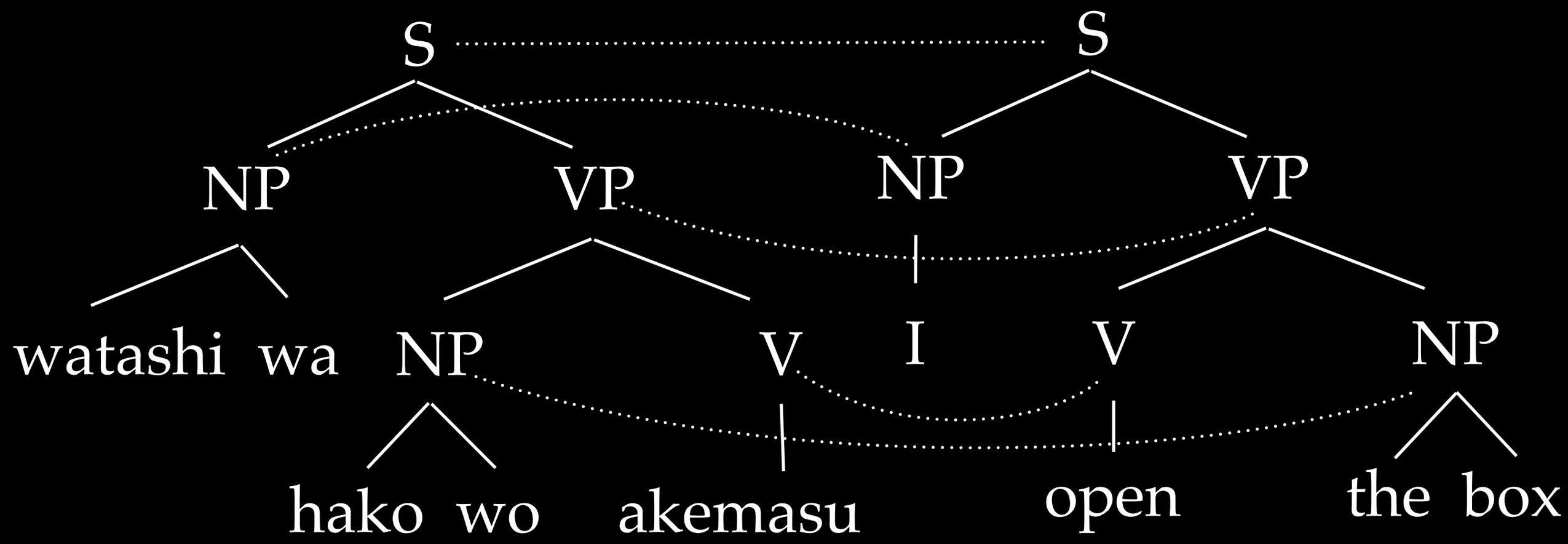


Synchronous Context-Free Grammar



watashi wa hako wo akemasu

Synchronous Context-Free Grammar



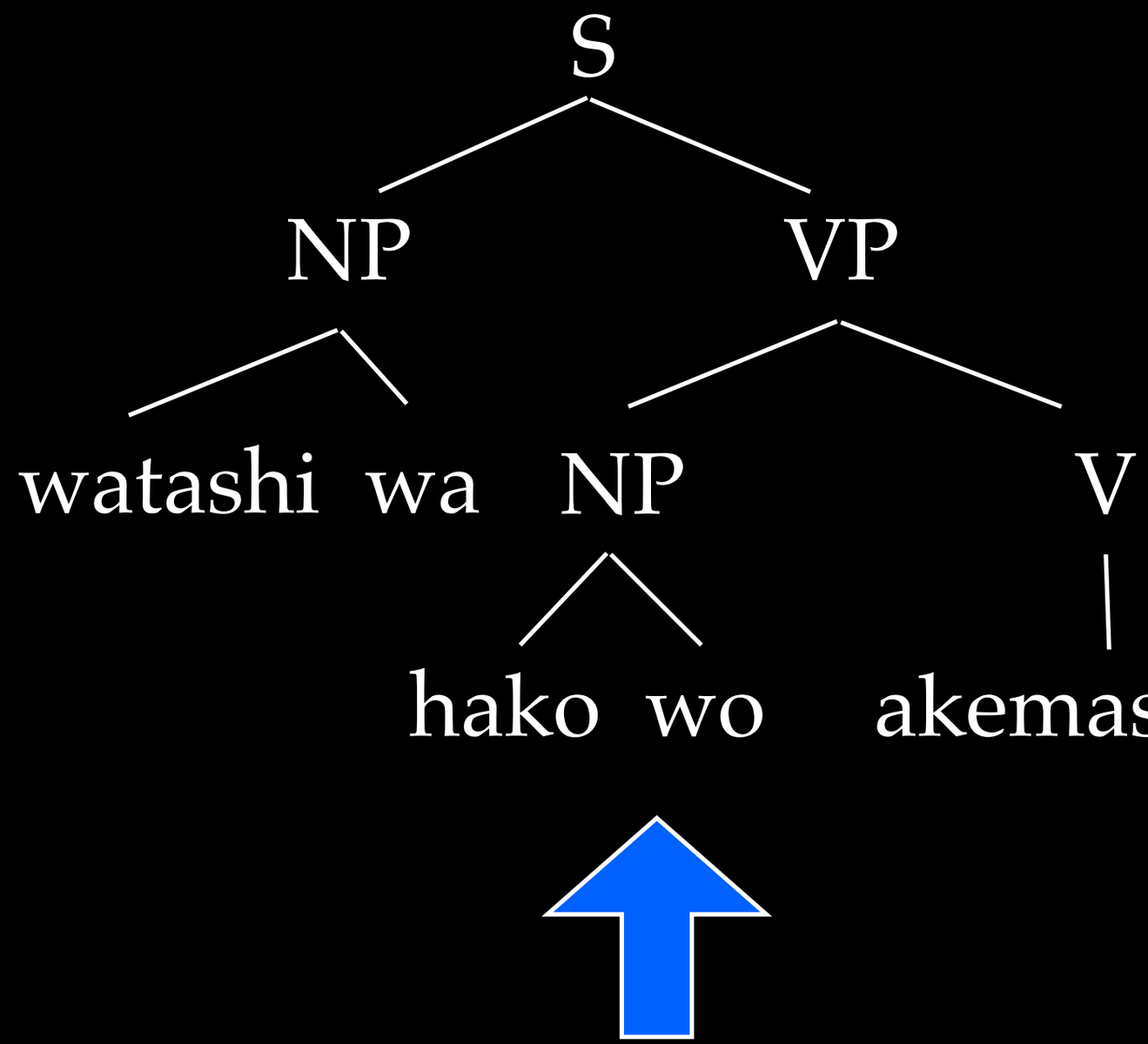
watashi wa hako wo akemasu

I open the box

Translation is Parsing

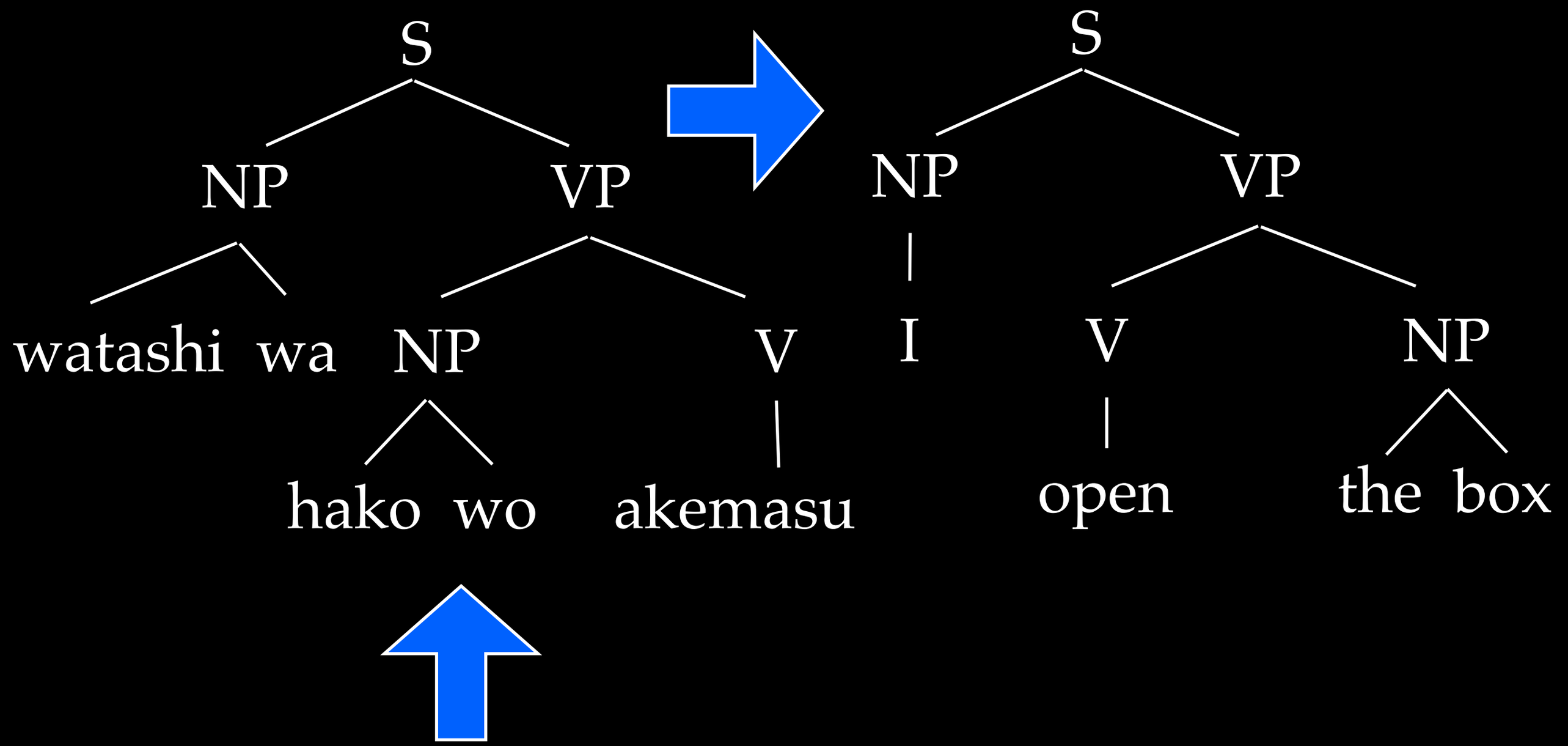
watashi wa hako wo akemasu

Translation is Parsing



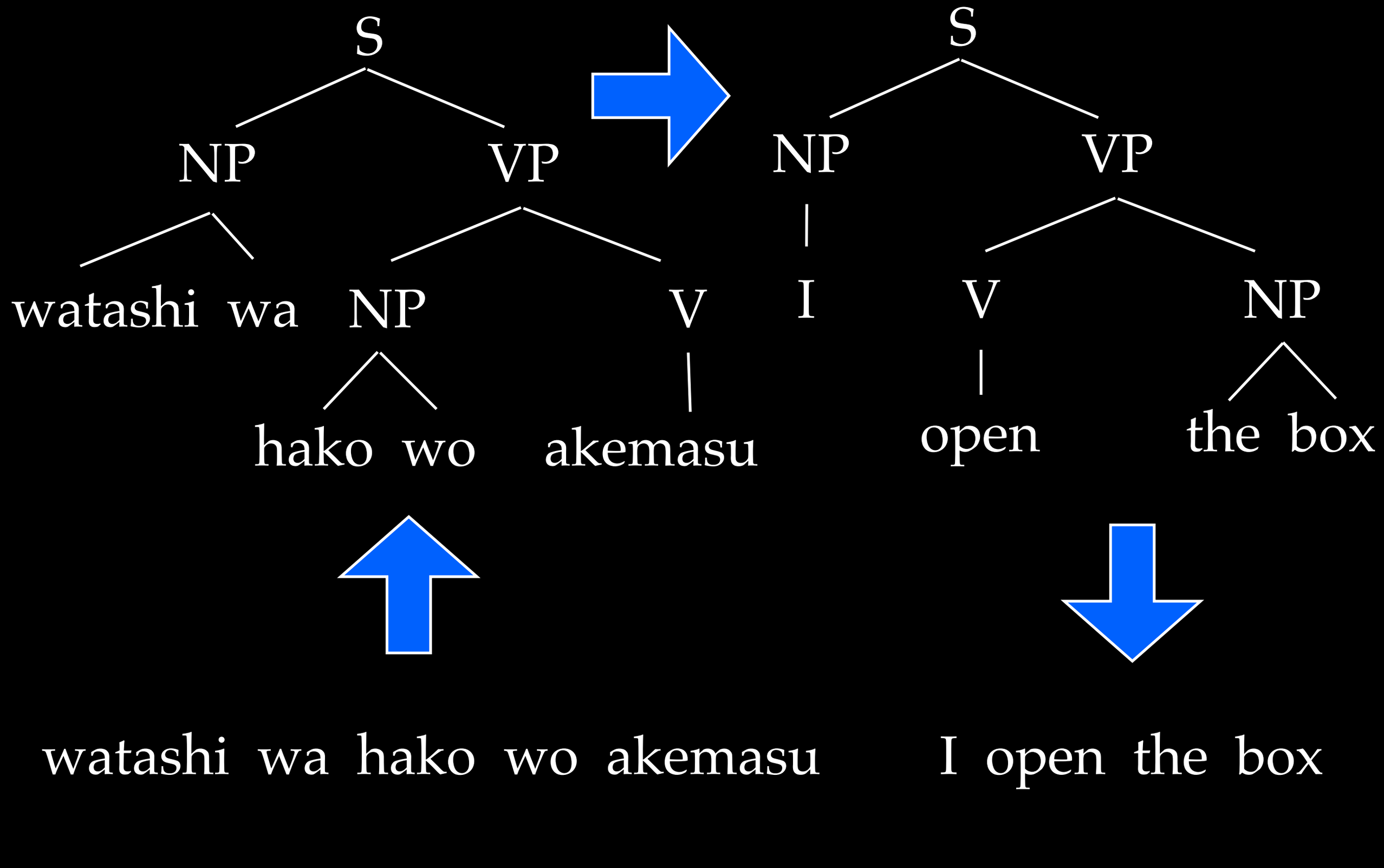
watashi wa hako wo akemasu

Translation is Parsing



watashi wa hako wo akemasu

Translation is Parsing



Translation is Parsing

Translation is Parsing

- How many parses of a sentence are there?

Translation is Parsing

- How many parses of a sentence are there?
- For binary grammar: Catalan number.

Translation is Parsing

- How many parses of a sentence are there?
- For binary grammar: Catalan number. $O(\frac{(2n)!}{(n+1)!n!})$

Translation is Parsing

- How many parses of a sentence are there?
  - For binary grammar: Catalan number. $O(\frac{(2n)!}{(n+1)!n!})$
- Dynamic programming to the rescue!

Parsing

Parsing

NN → duck

NP → PRP$ NN

PRP → her

PRP → I

PRP$ → her

S → PRP VP

SBAR → PRP VB

VB → duck

VP → VBD NP

VP → VBD SBAR

VBD → saw

Parsing

NN → duck

NP → PRP$ NN

PRP → her

PRP → I

PRP$ → her

S → PRP VP

SBAR → PRP VB

VB → duck

VP → VBD NP

VP → VBD SBAR

VBD → saw

I_1 saw_2 her_3 $duck_4$

Parsing

NN → duck

NP → PRP$ NN

PRP → her

PRP → I

PRP$ → her

S → PRP VP

SBAR → PRP VB

VB → duck

VP → VBD NP

VP → VBD SBAR

VBD → saw

$$X_{i,i+1} \leftarrow (w_{i+1} = w) \wedge (X \rightarrow w)$$

I_1 saw_2 her_3 duck_4

Parsing

NN → duck

NP → PRP$ NN

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SBAR → PRP VB

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$$X_{i,i+1} \leftarrow (w_{i+1} = w) \wedge (X \rightarrow w)$$

I$_1$ saw$_2$ her$_3$ duck$_4$

Parsing

NN → duck

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SBAR → PRP VB

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I$_1$ saw$_2$ her$_3$ duck$_4$

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$$X_{i,i+1} \leftarrow (w_{i+1} = w) \wedge (X \rightarrow w)$$

$$PRP_{0,1} \leftarrow (w_1 = \mathrm{I}) \wedge (PRP \rightarrow \mathrm{I})$$

I_1 saw_2 her_3 duck_4

Parsing

NN → duck

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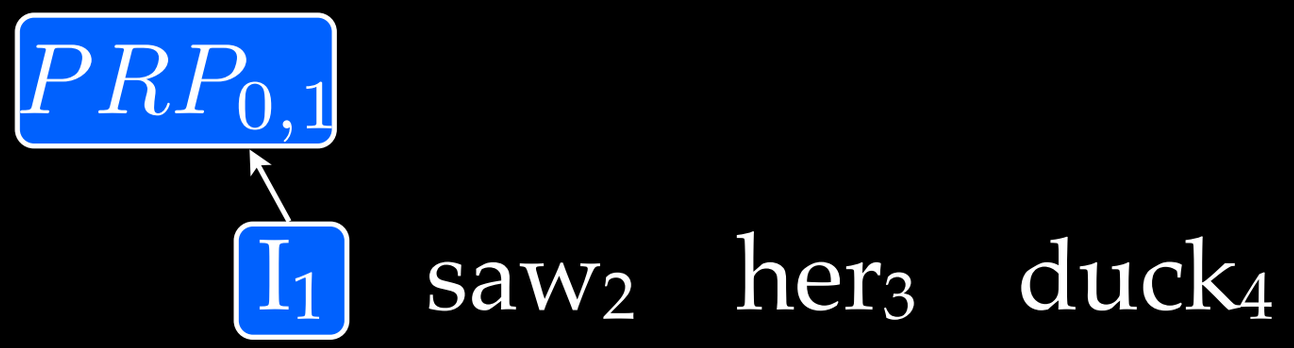

Parsing

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$$X_{i,i+1} \leftarrow (w_{i+1} = w) \wedge (X \rightarrow w)$$

$PRP_{0,1}$

I$_1$ saw$_2$ her$_3$ duck$_4$

Parsing

NN → duck

NP → PRP$ NN

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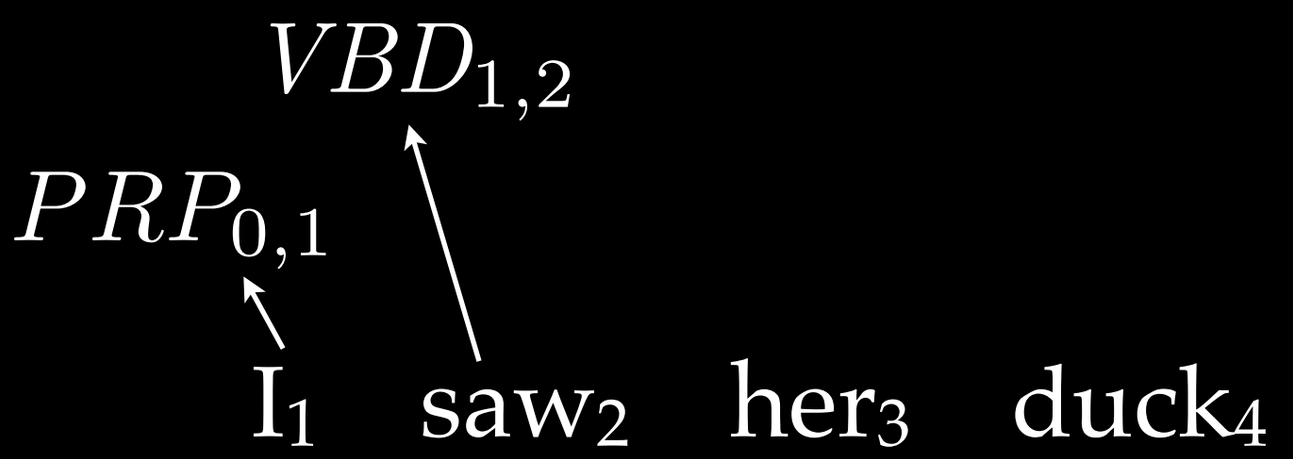

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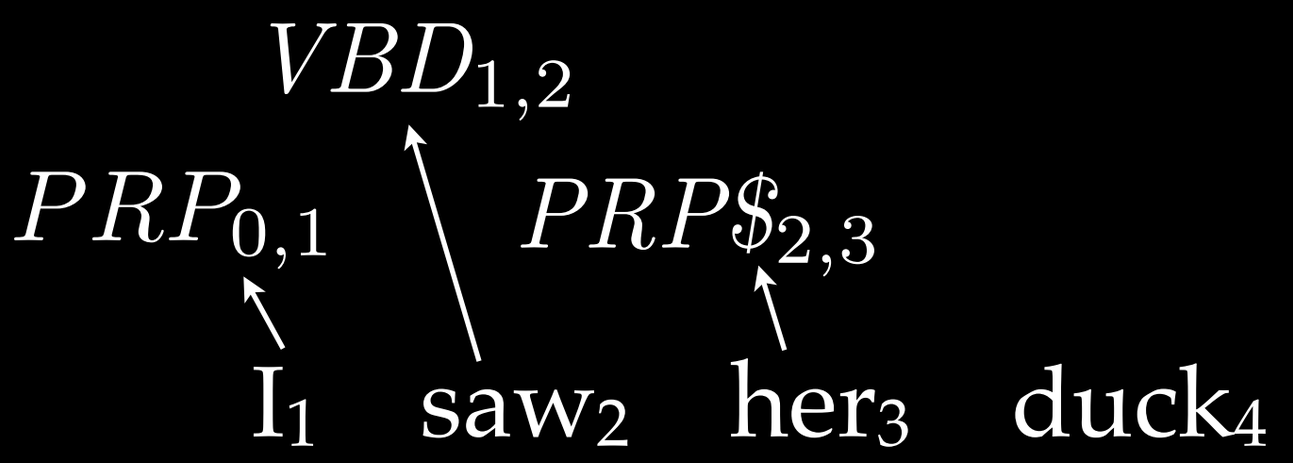

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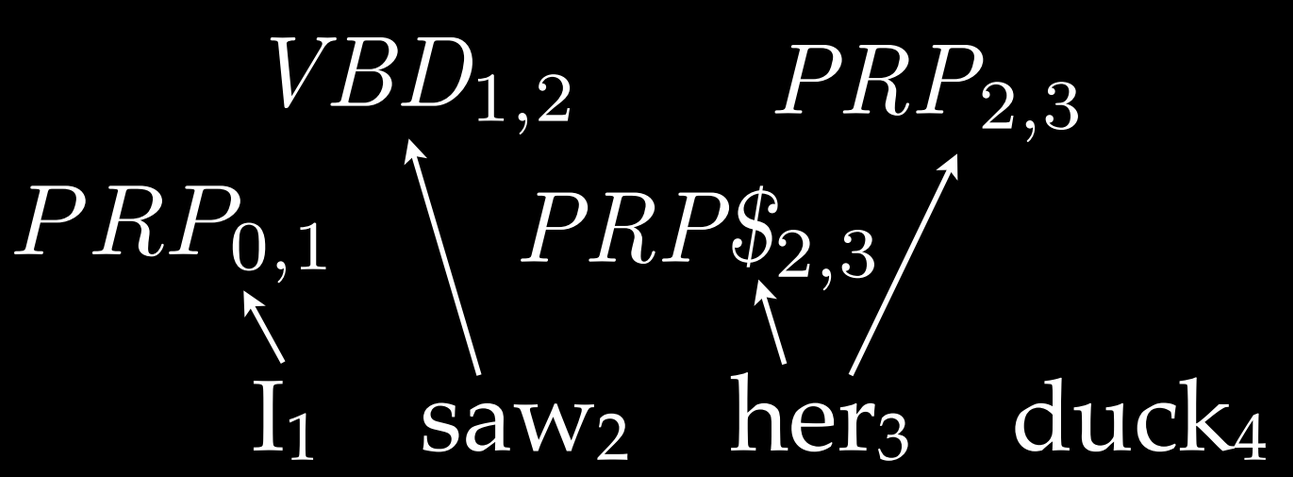

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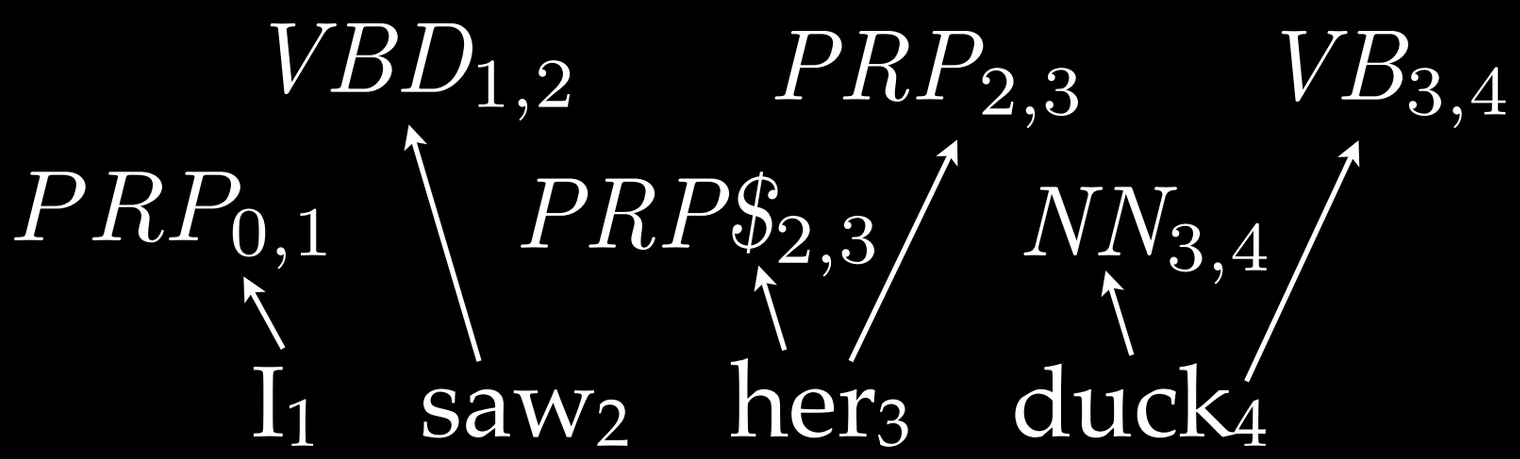

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SBAR → PRP VB

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$$X_{i,i+1} \leftarrow (w_{i+1} = w) \wedge (X \rightarrow w)$$

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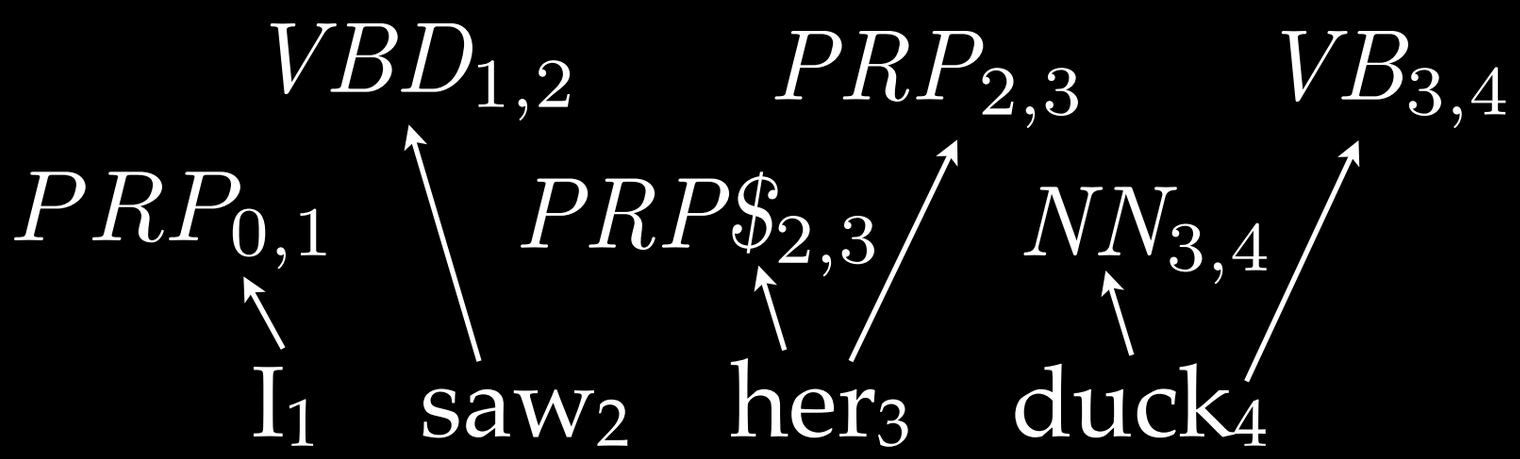

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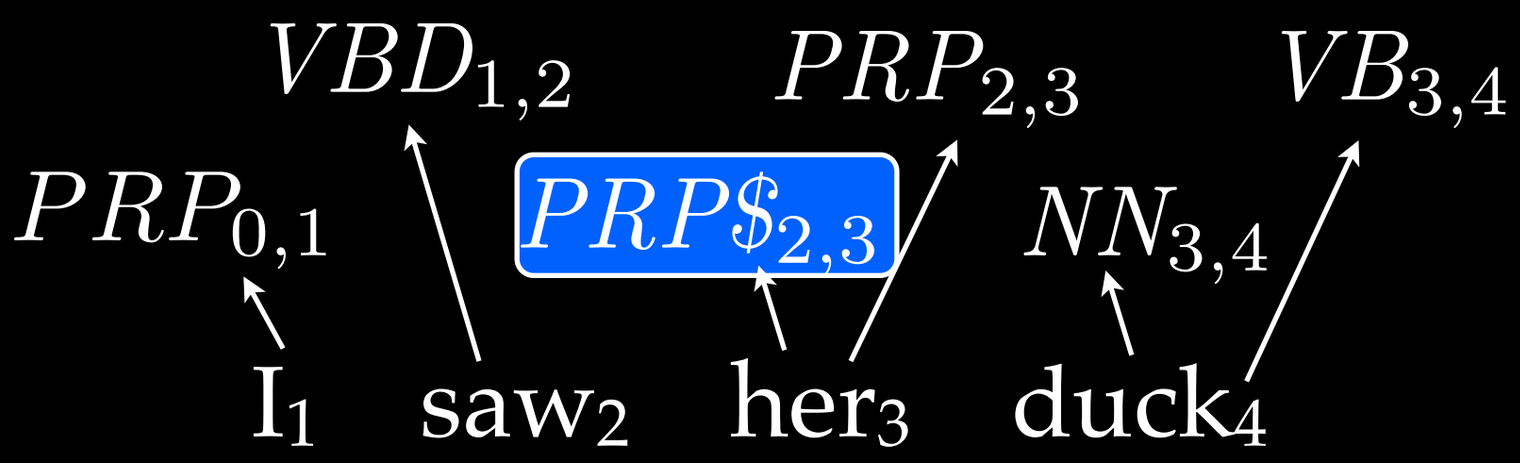

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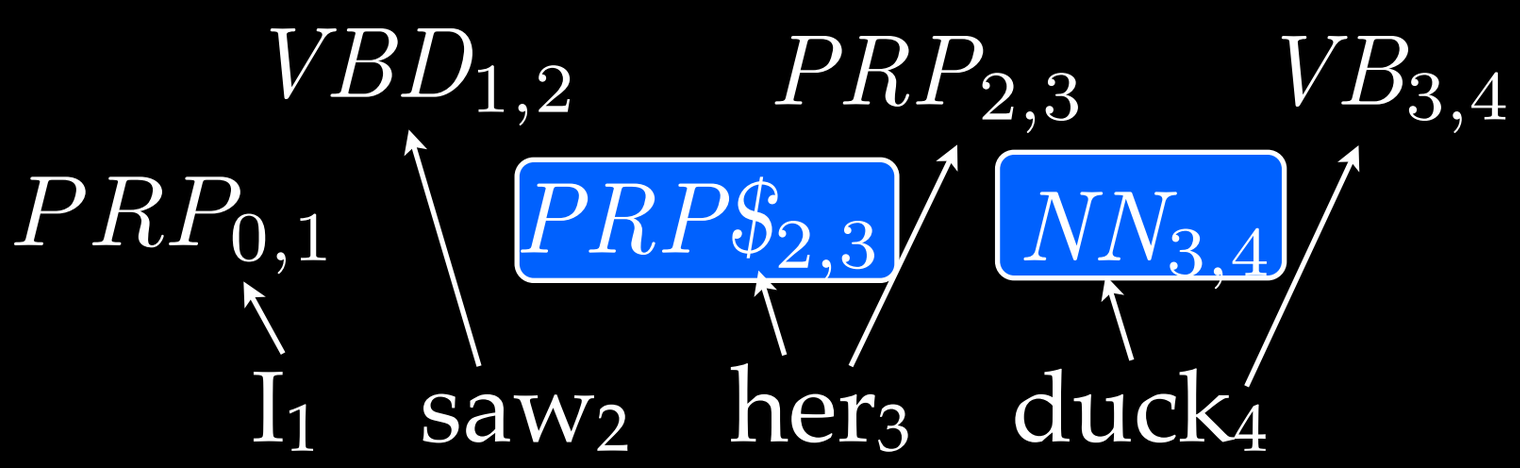

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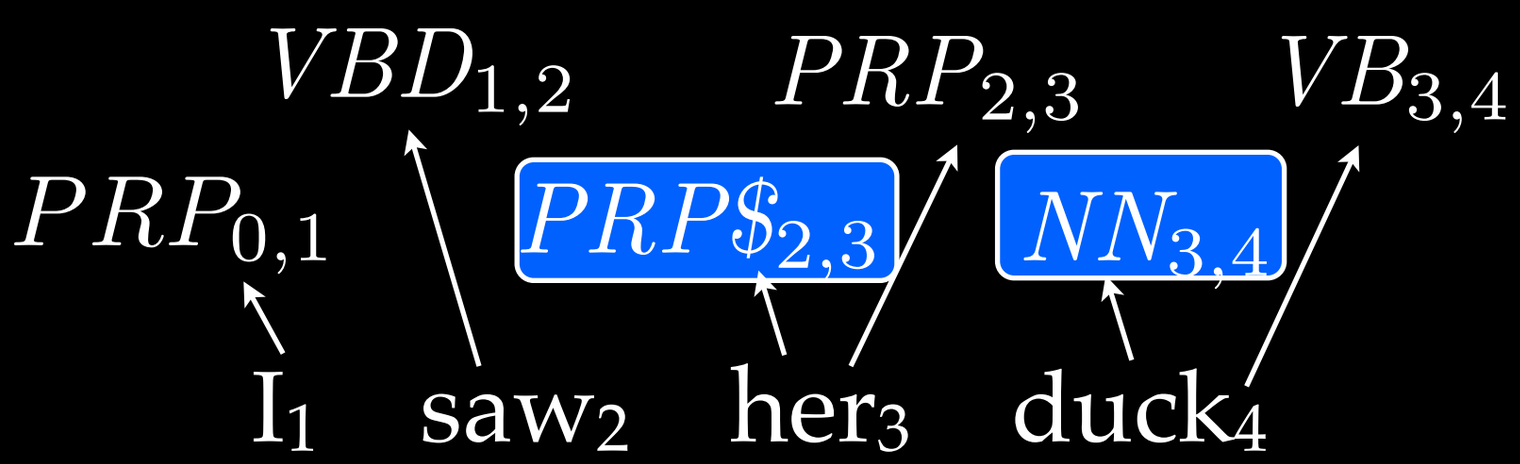

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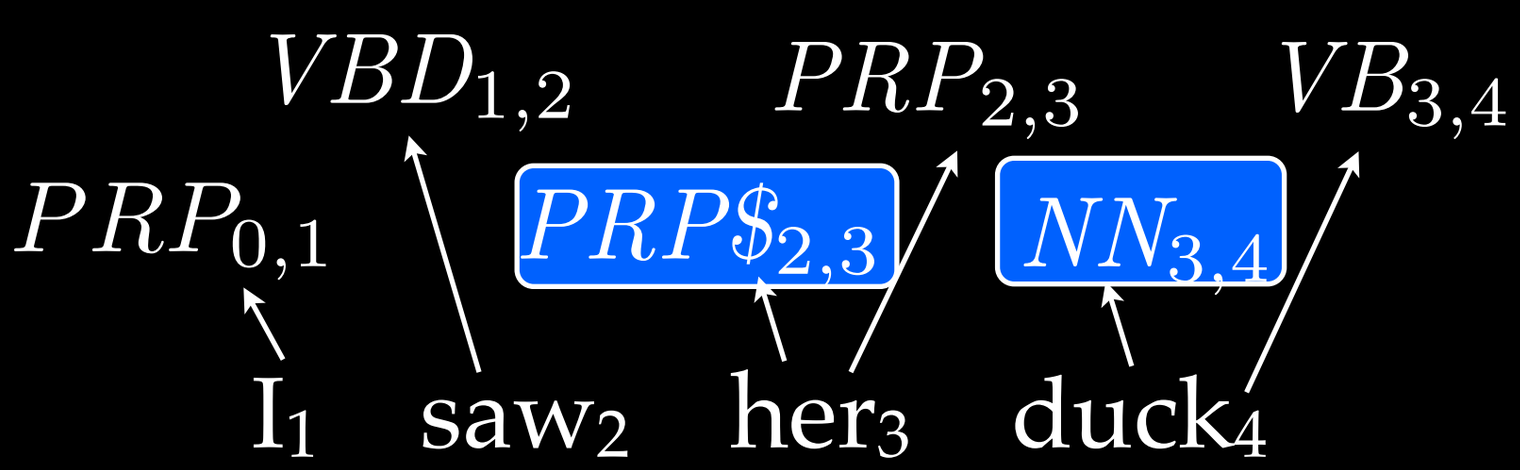

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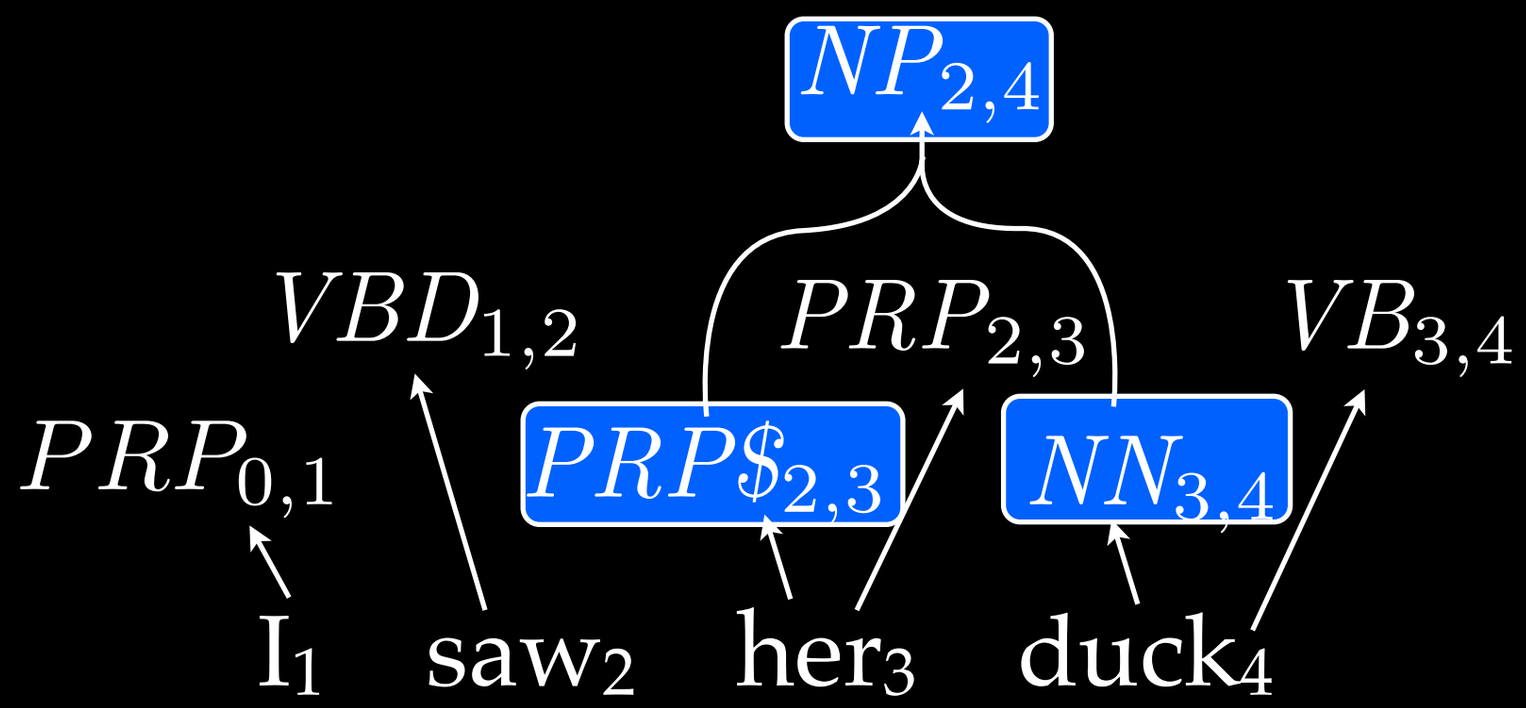

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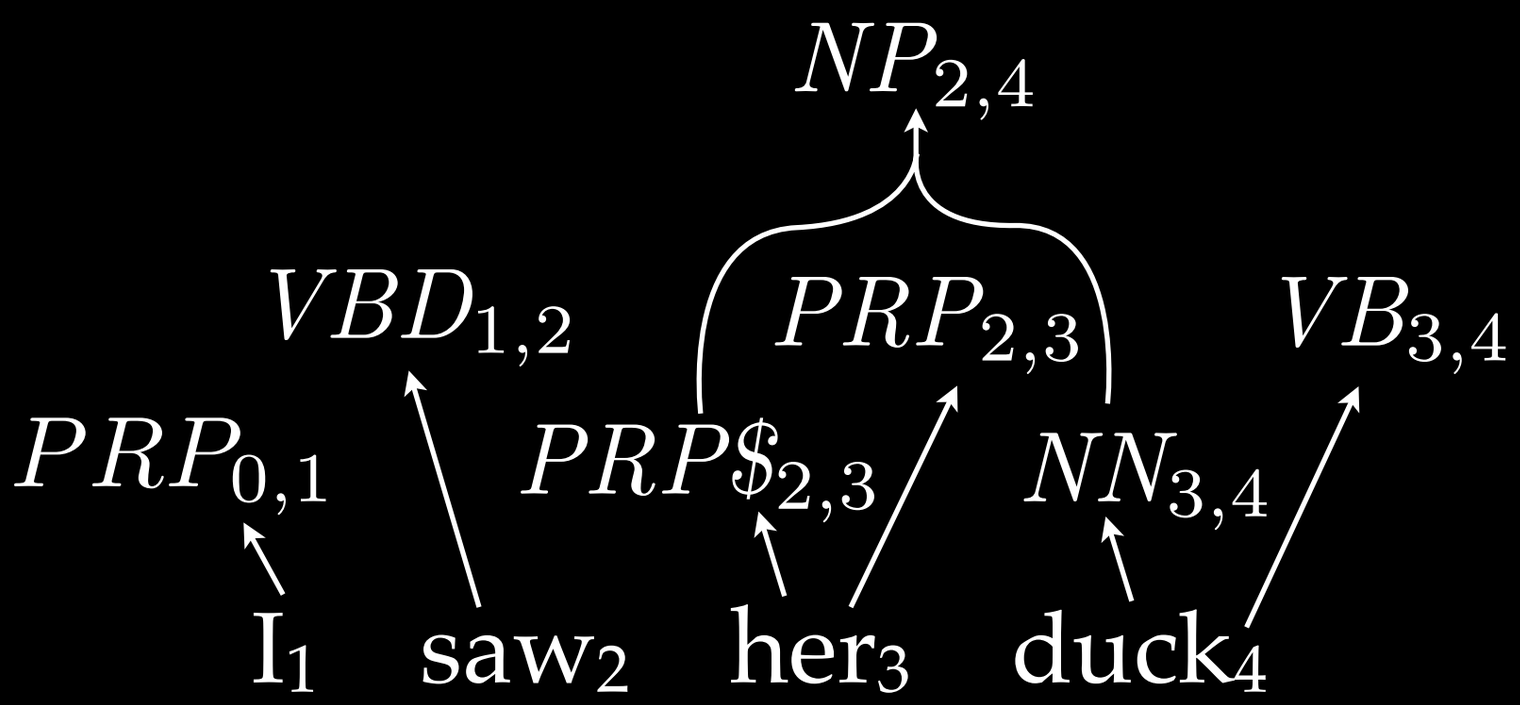

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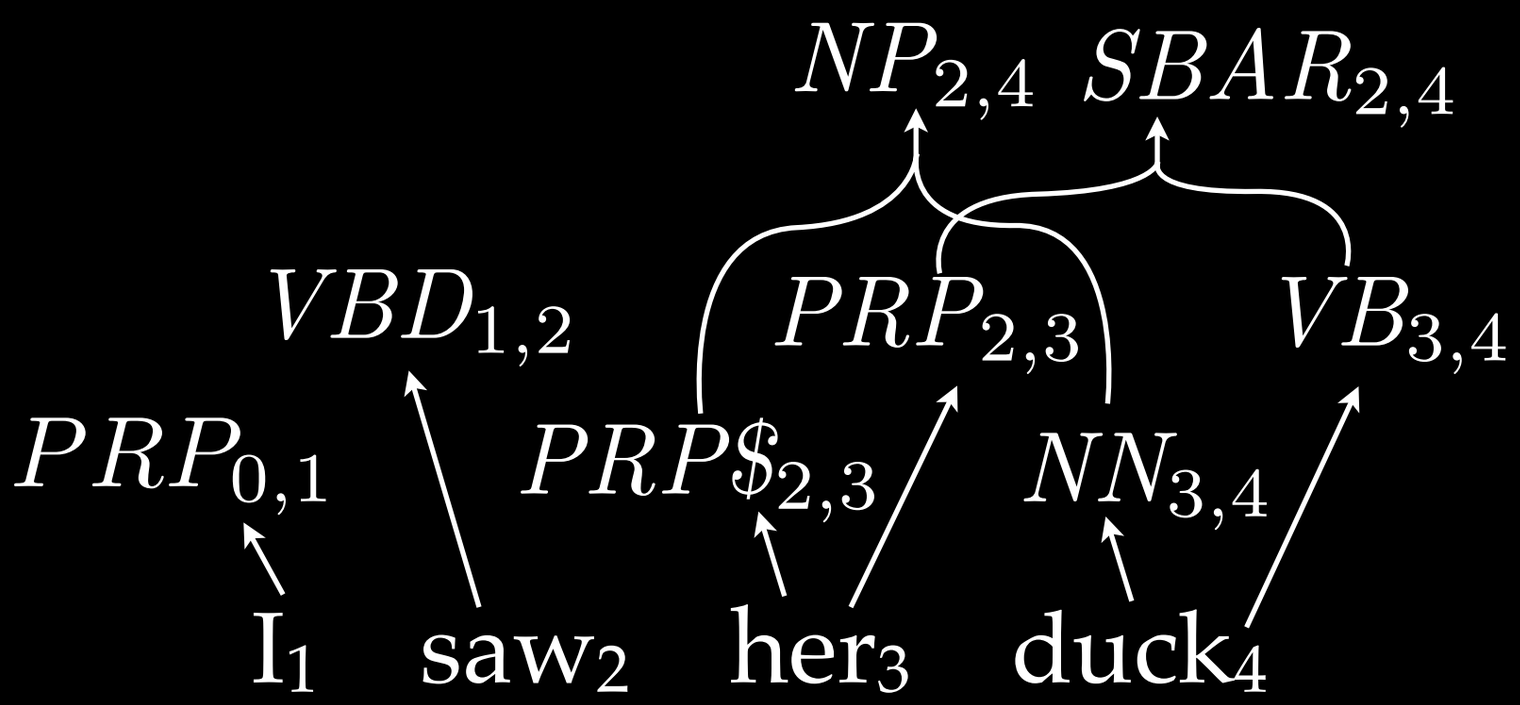

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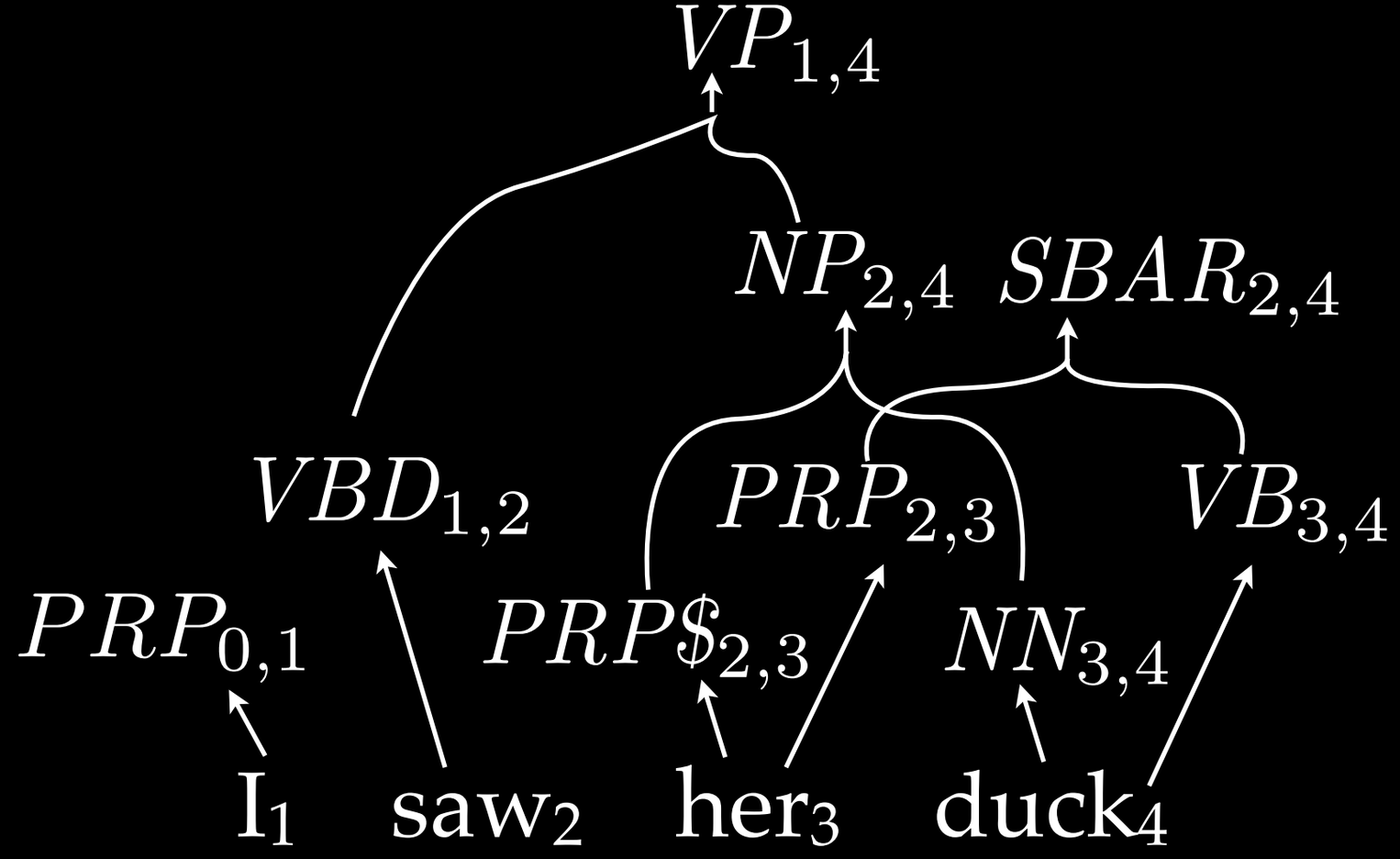

Parsing

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PRP → her
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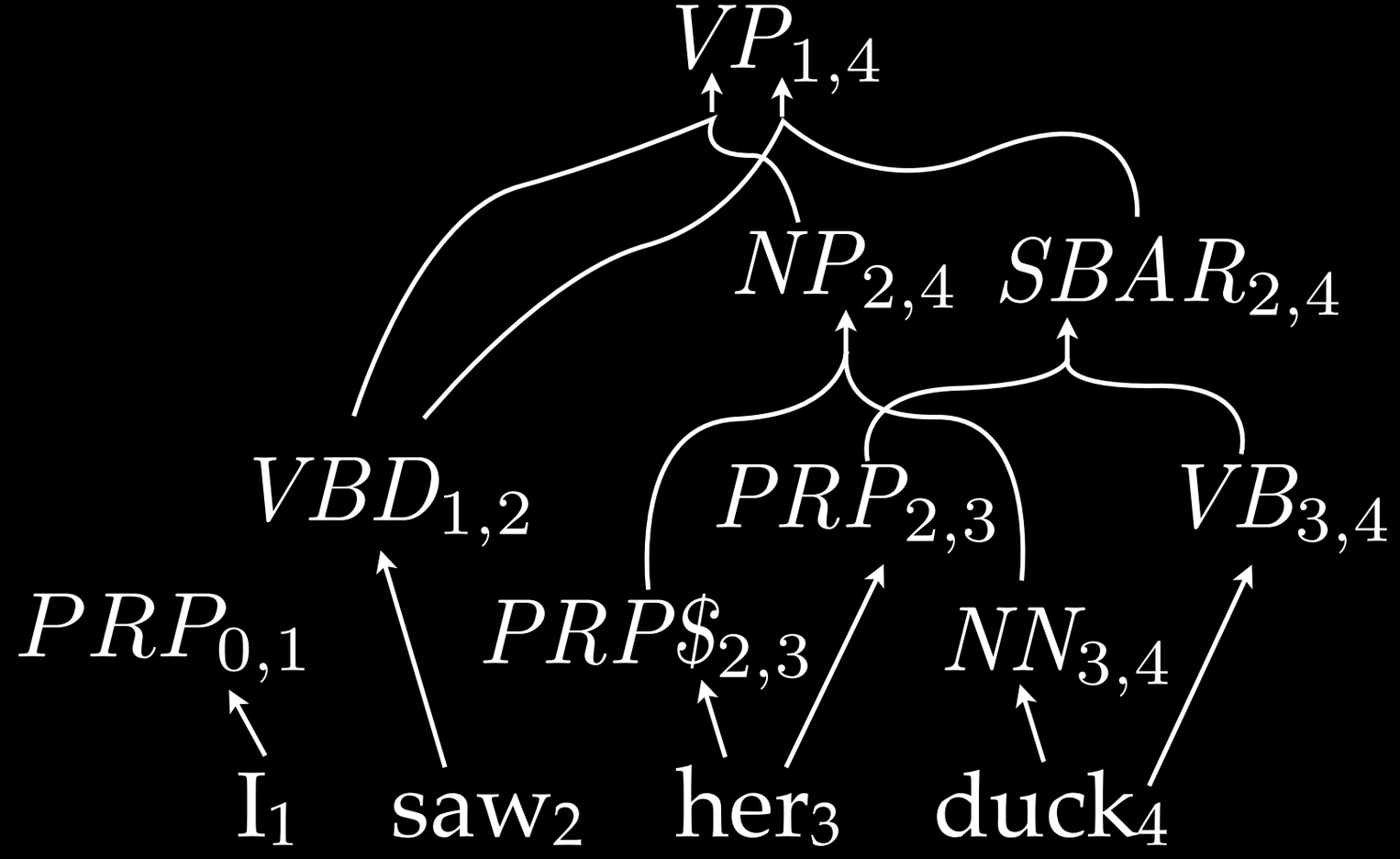

Parsing

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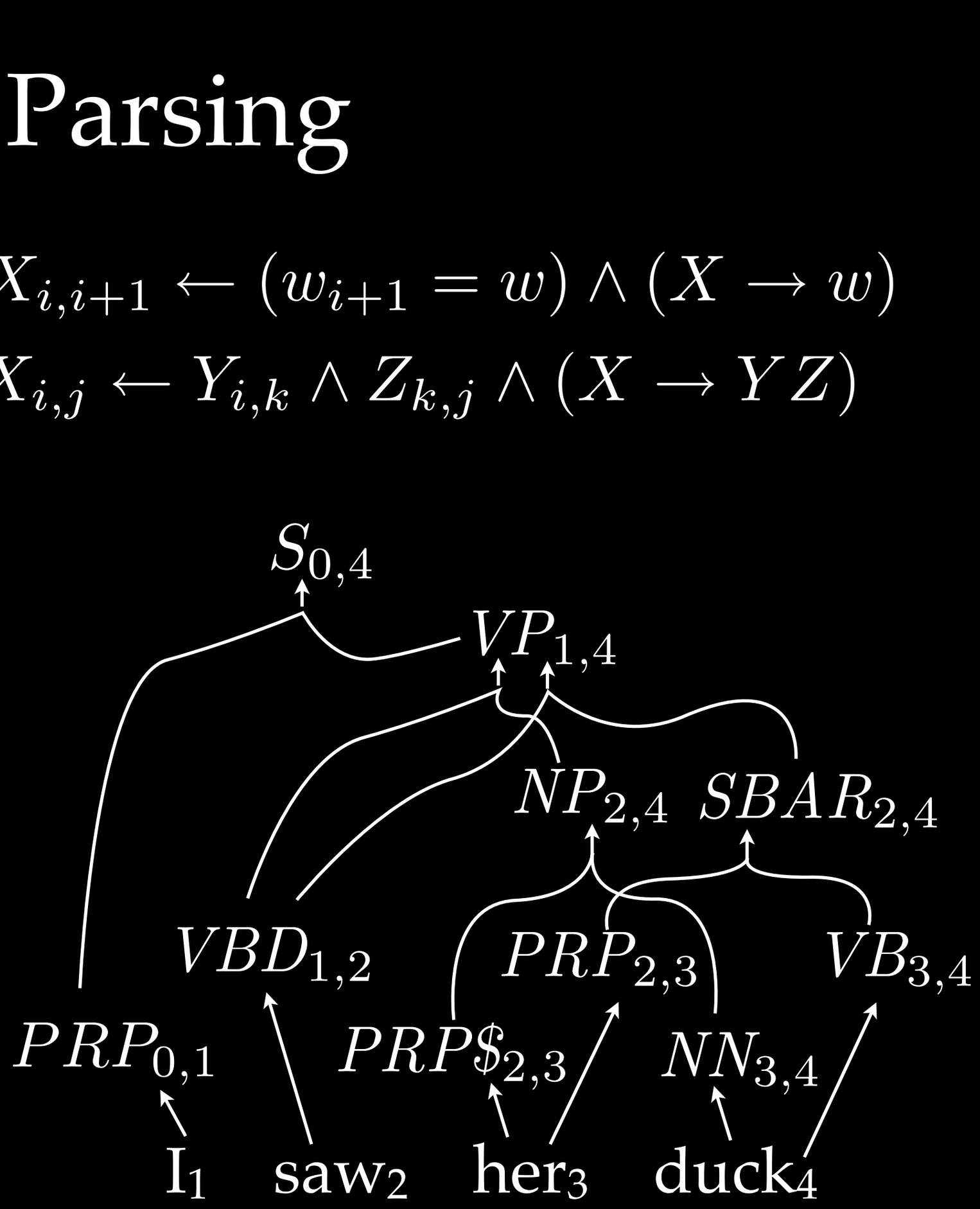
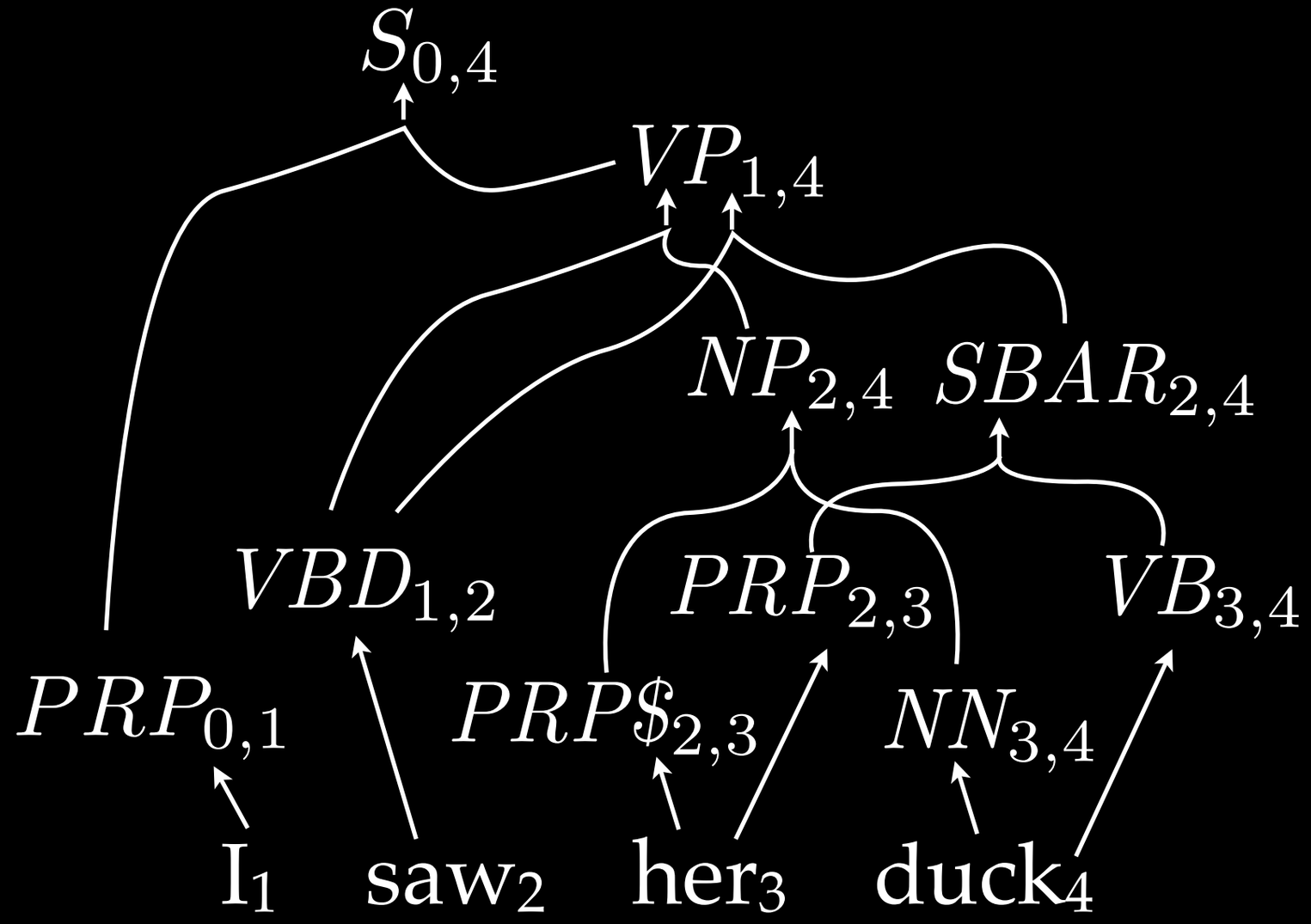
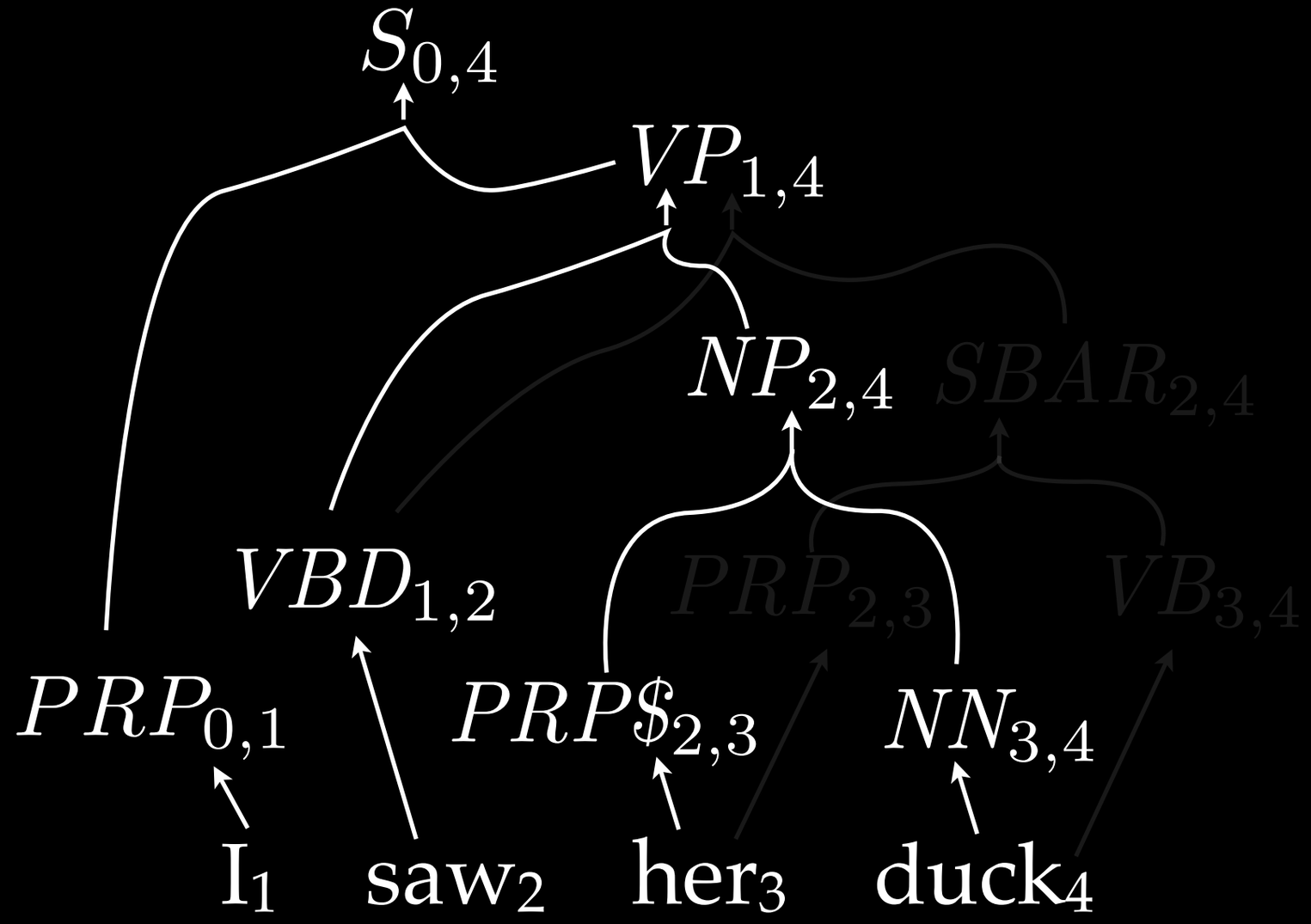


Parsing


$S_{0,4}$
$VP_{1,4}$
$NP_{2,4}$
$SBAR_{2,4}$
$VBD_{1,2}$
$PRP_{2,3}$
$VB_{3,4}$
$PRP_{0,1}$
$PRP\$_{2,3}$
$NN_{3,4}$
I_1
saw_2
her_3
$duck_4$

Parsing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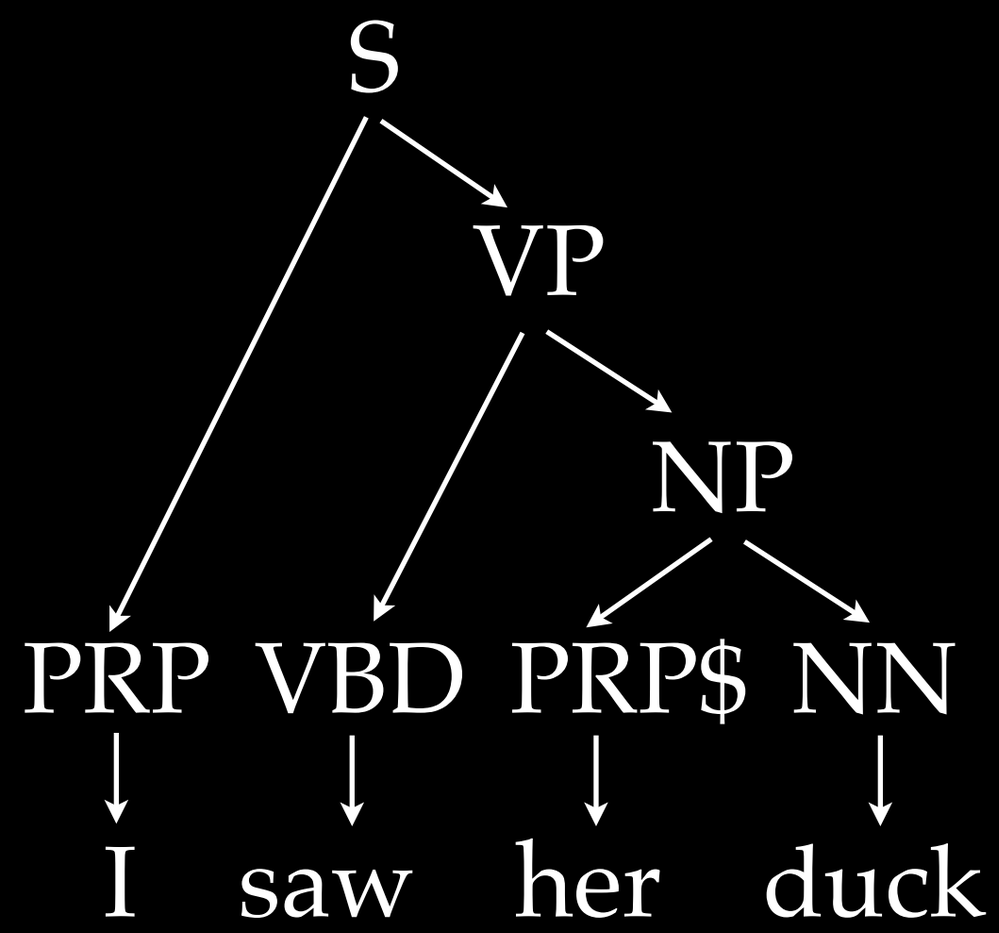
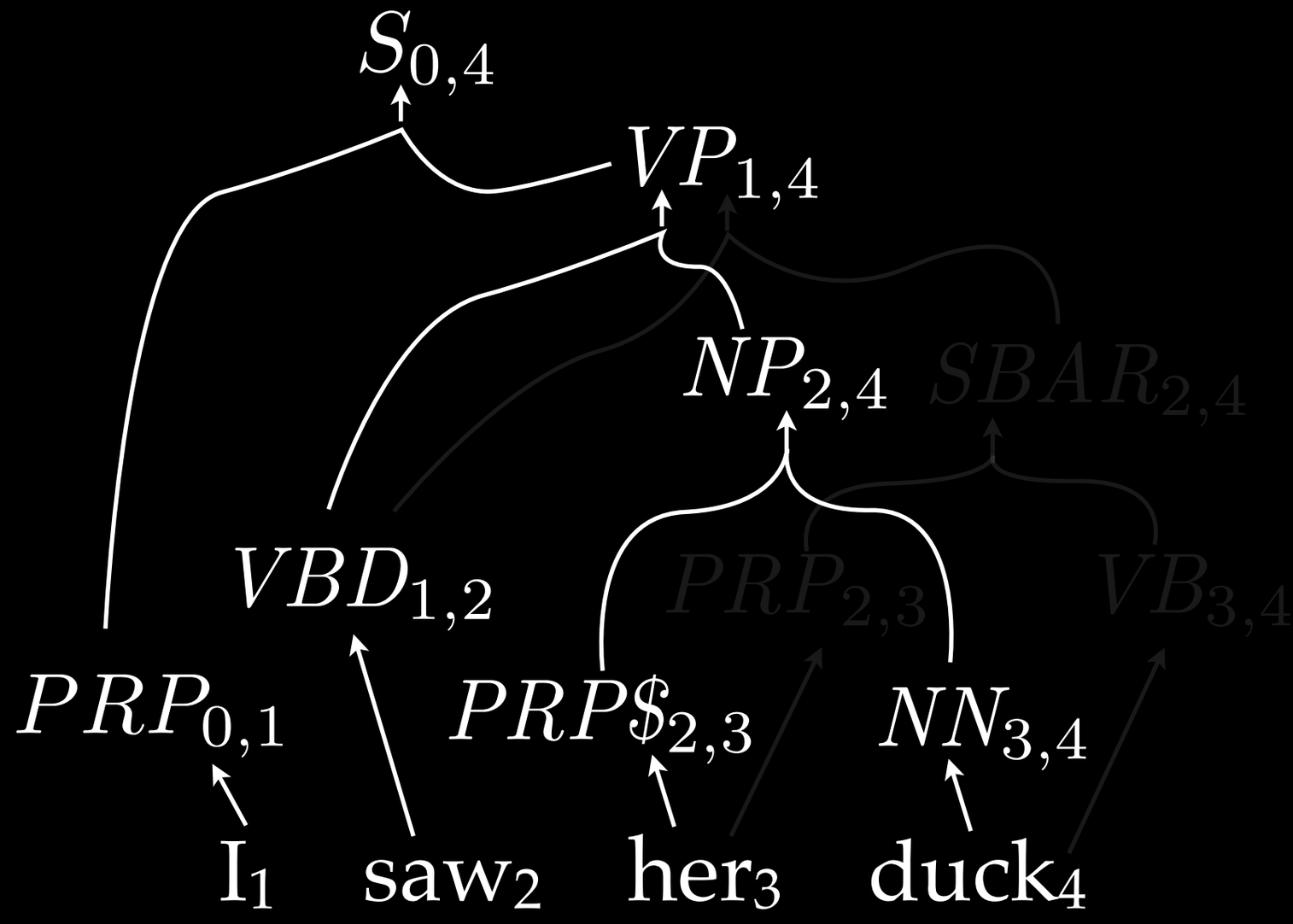
Parsing


S
VP
NP
PRP
VBD
PRP$
NN
I
saw
her
duck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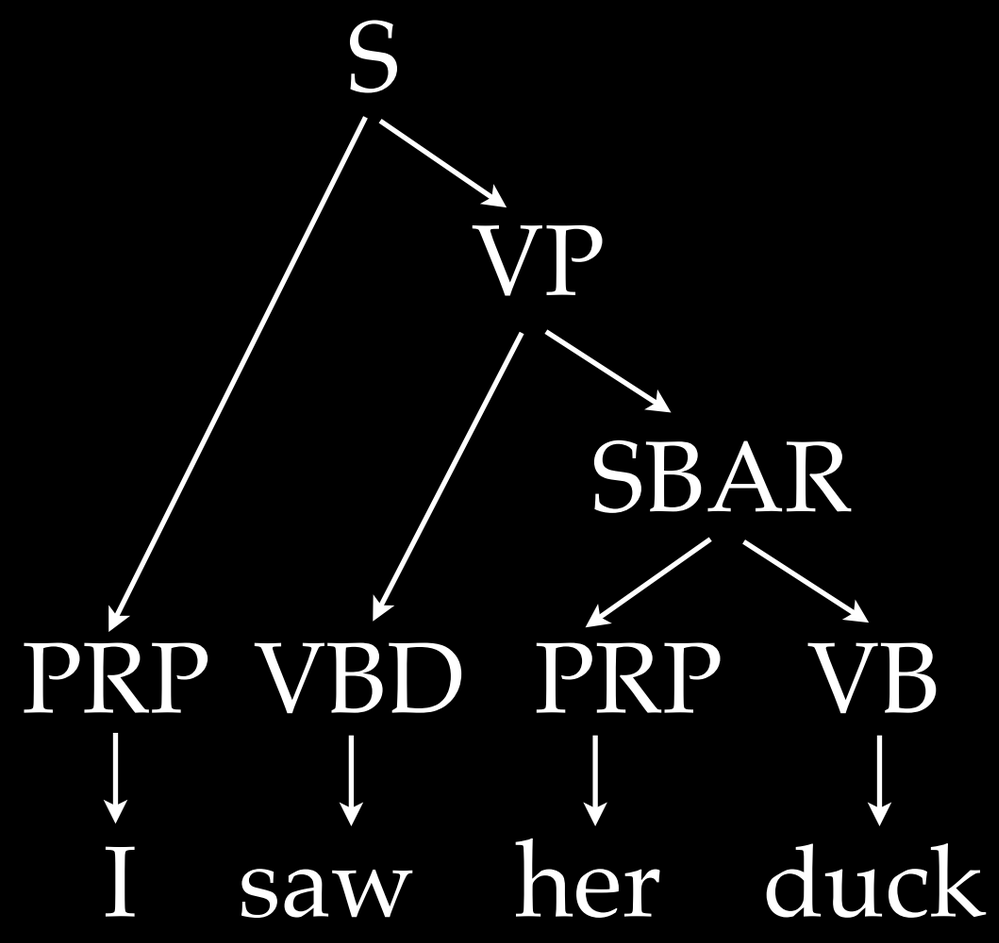
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PRP
VBD
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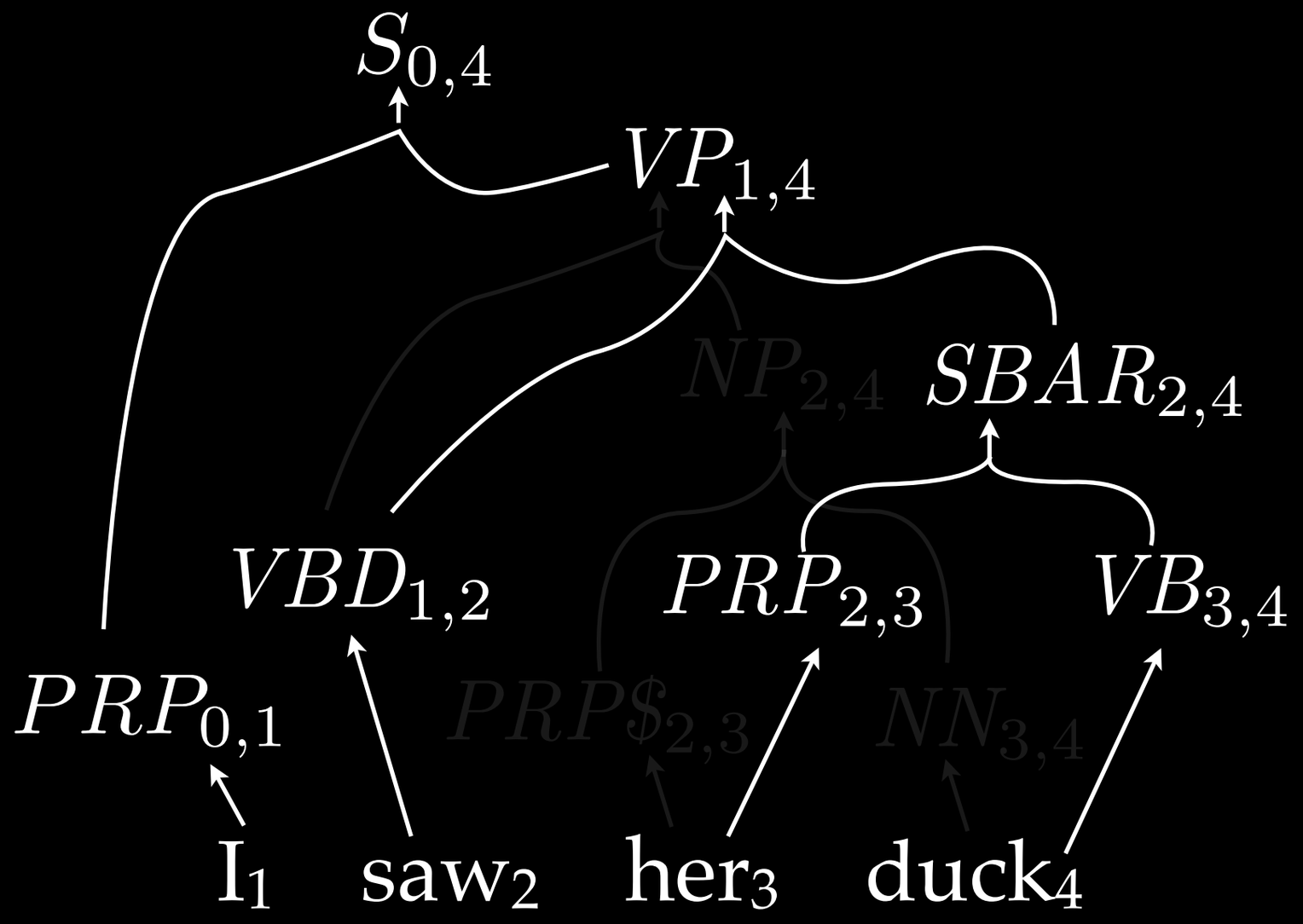
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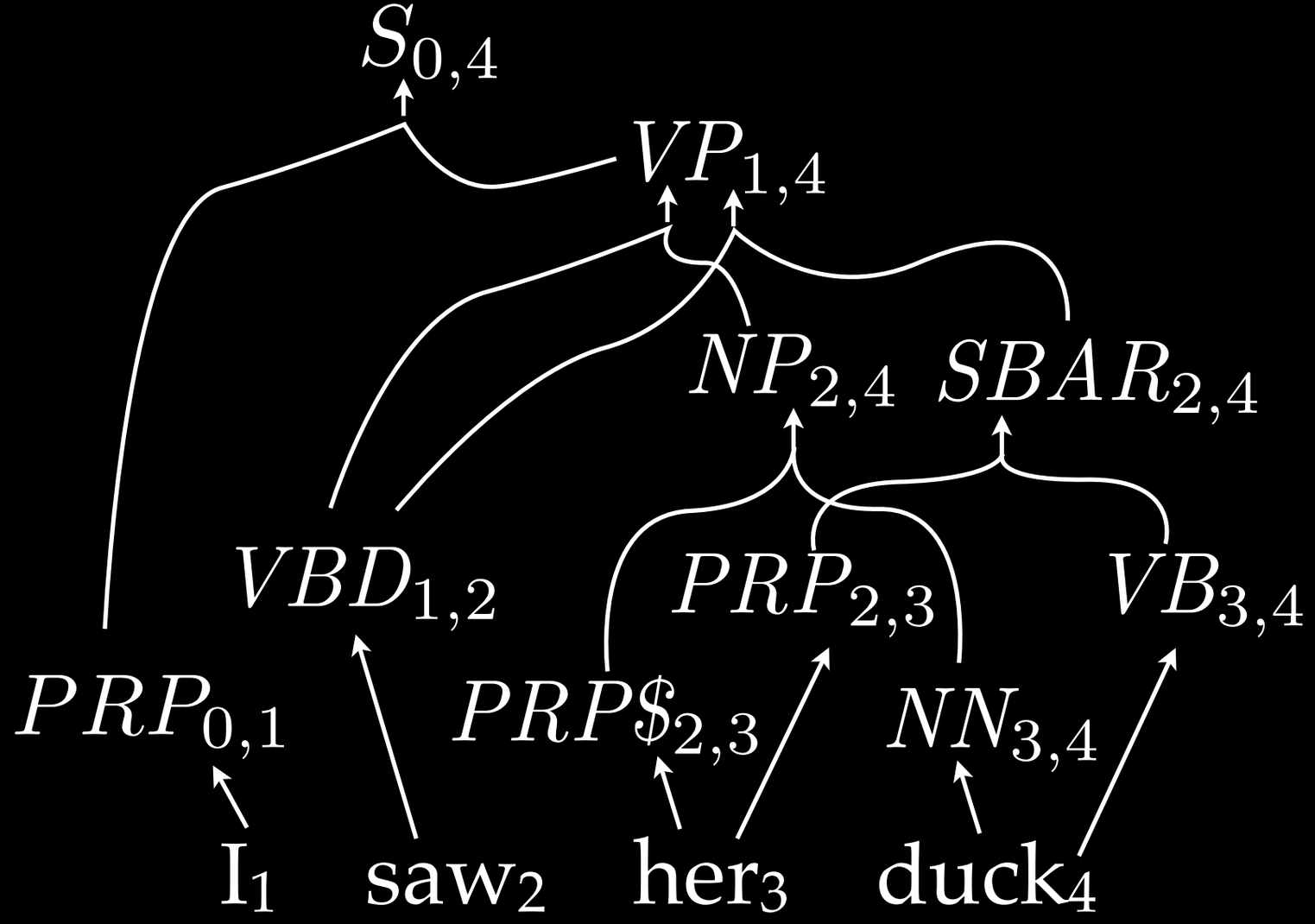
Parsing

Analysis

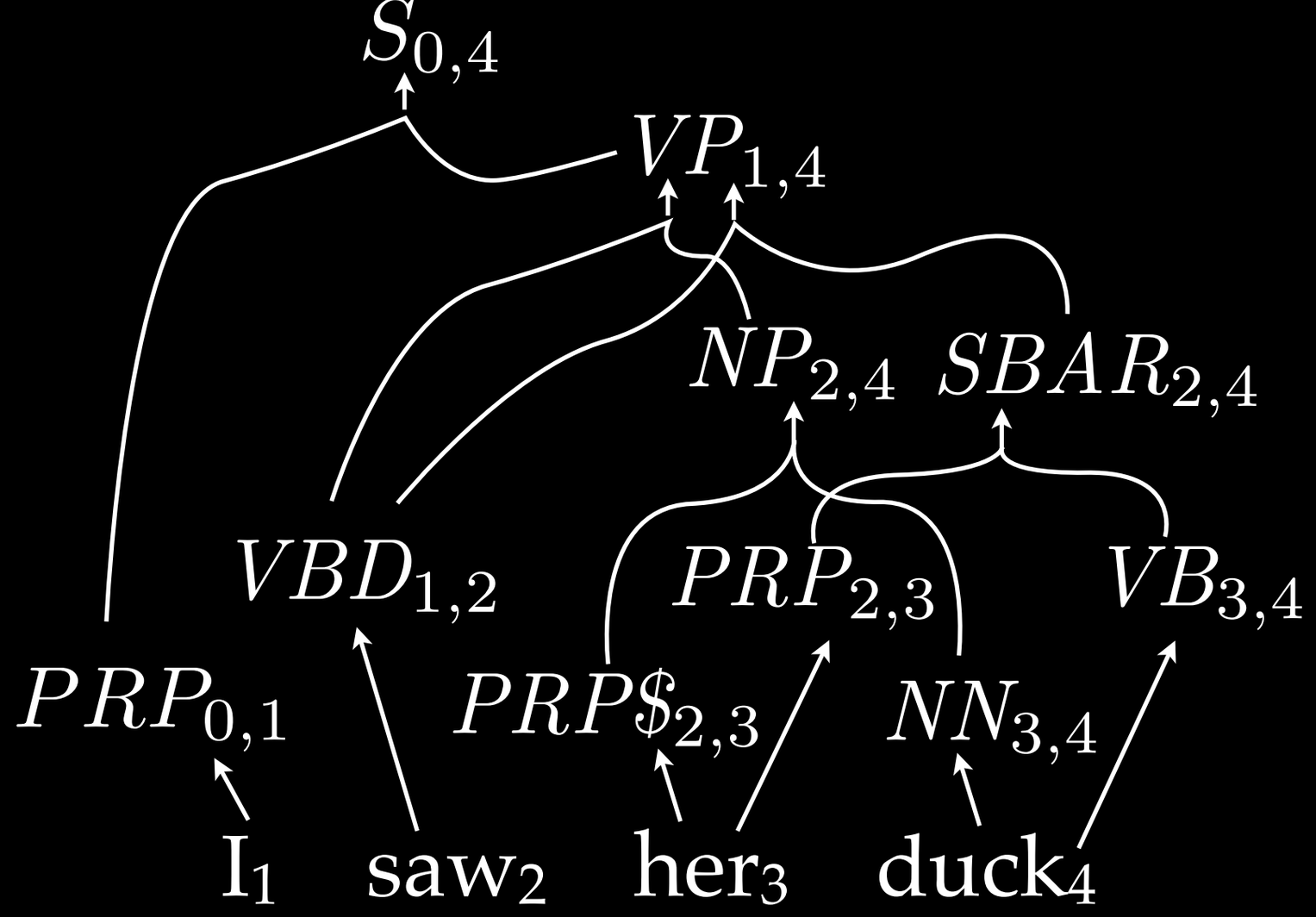


Parsing

Analysis

$O(Nn^2)$ nodes

$O(Gn^3)$ edges



Probabilistic Parsing

NN → duck

NP → PRP$ NN

PRP → her

PRP → I

PRP$ → her

S → PRP VP

SBAR → PRP VB

VB → duck

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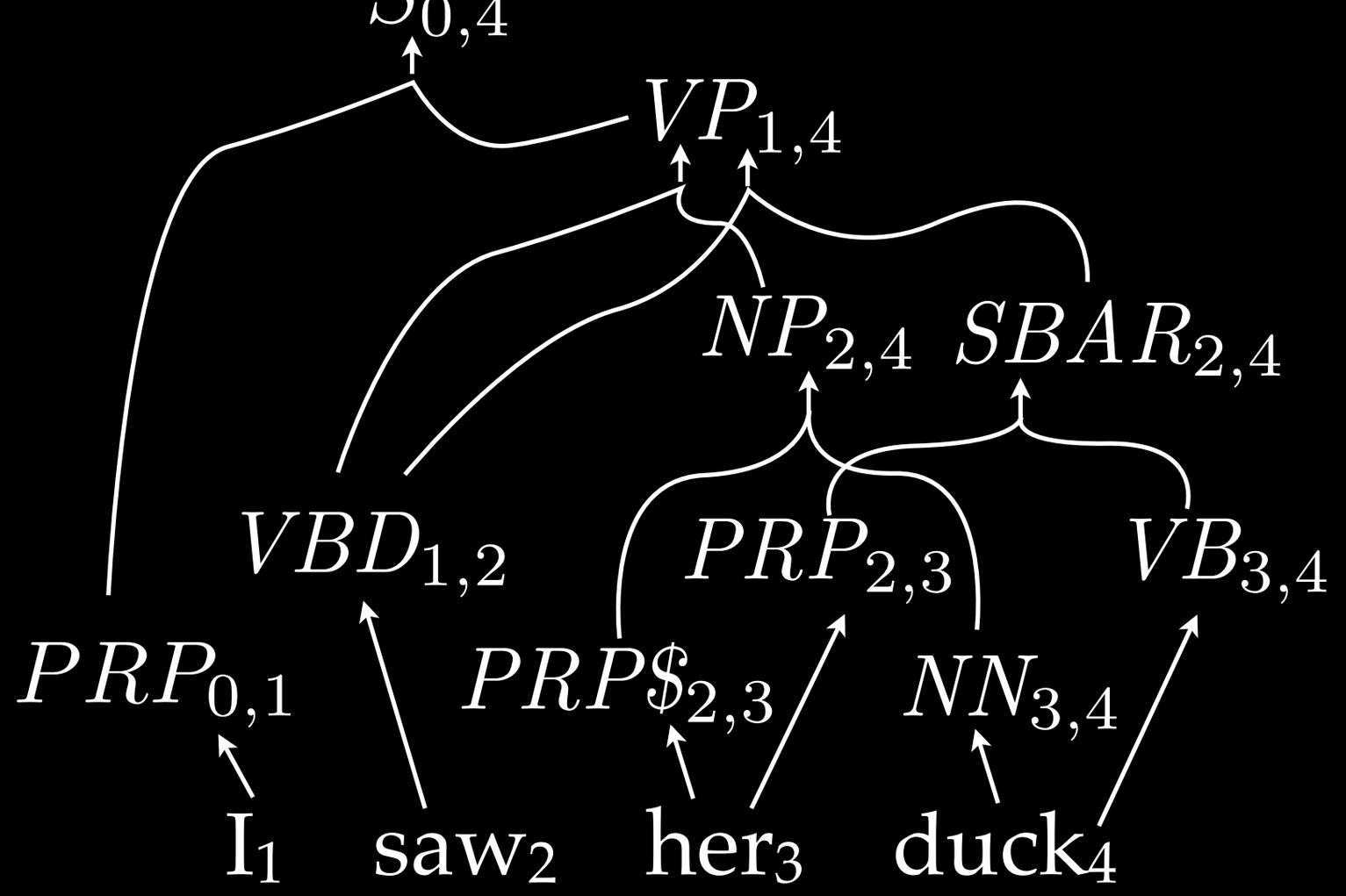
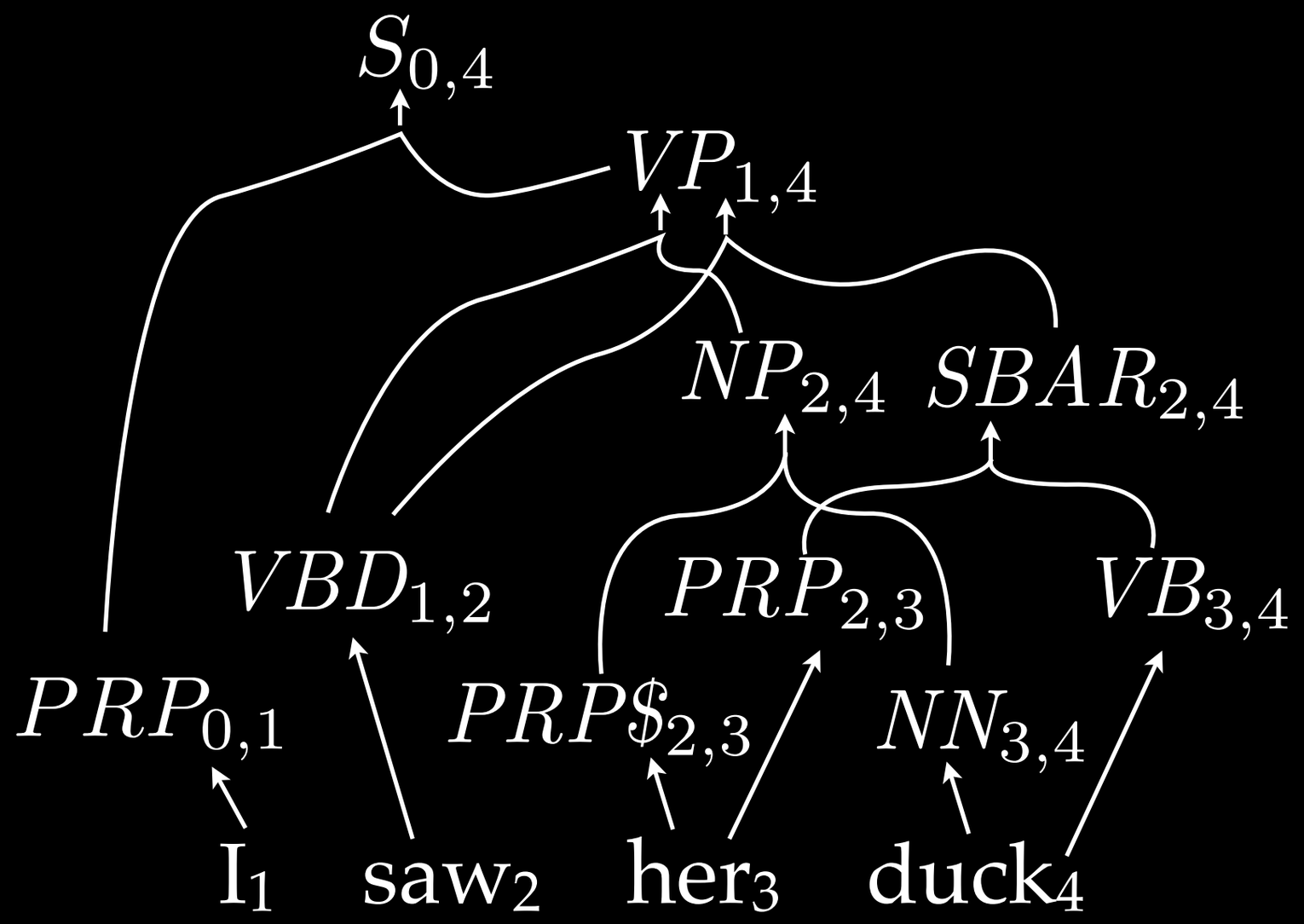
VP → VBD SBAR

VBD → saw



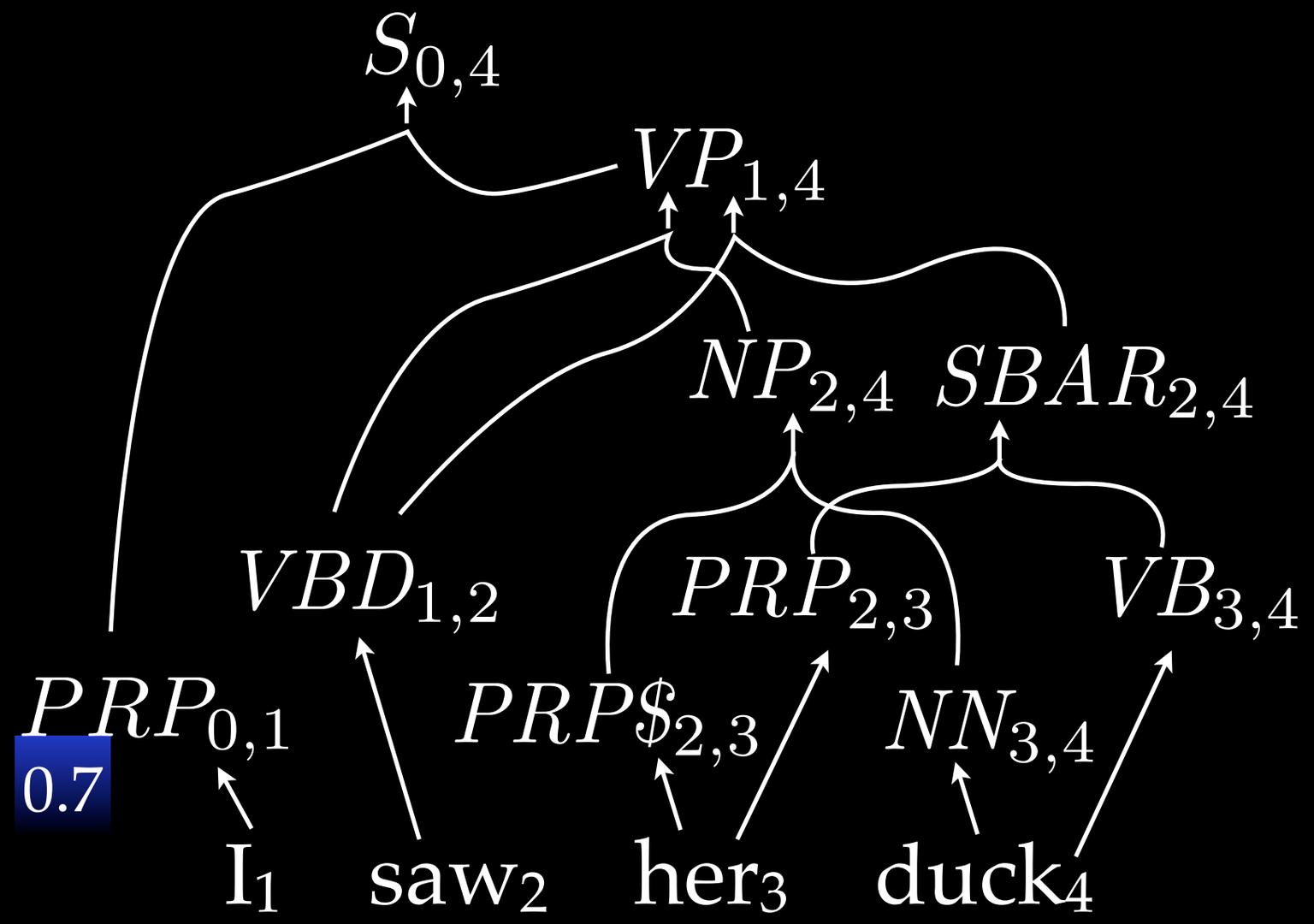
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



Probabilistic Parsing

NN → duck (1.0)

NP → PRP$ NN (1.0)

PRP → her (0.3)

PRP → I (0.7)

PRP$ → her (1.0)

S → PRP VP (1.0)

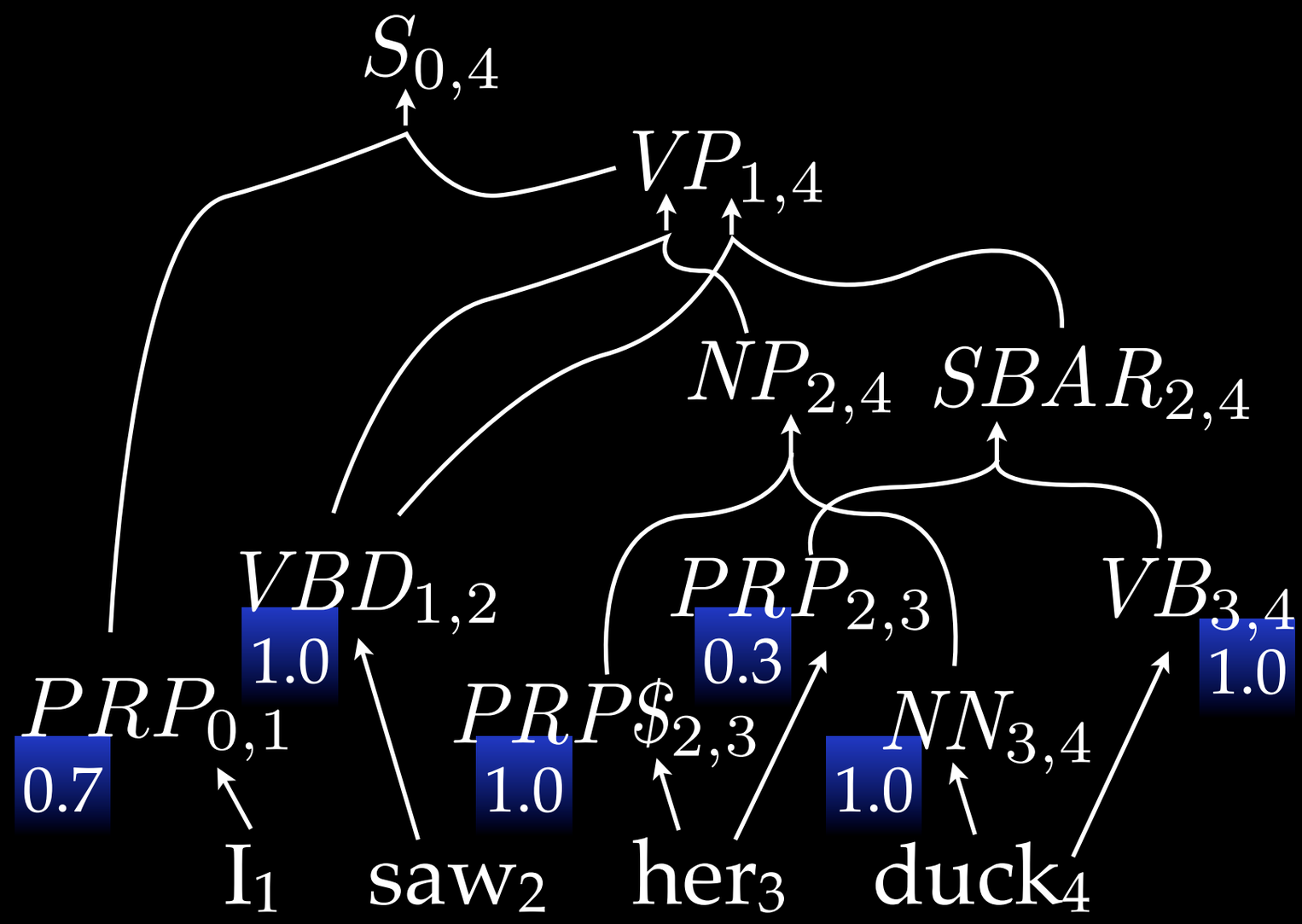
SBAR → PRP VB (1.0)

VB → duck (1.0)

VP → VBD NP (0.8)

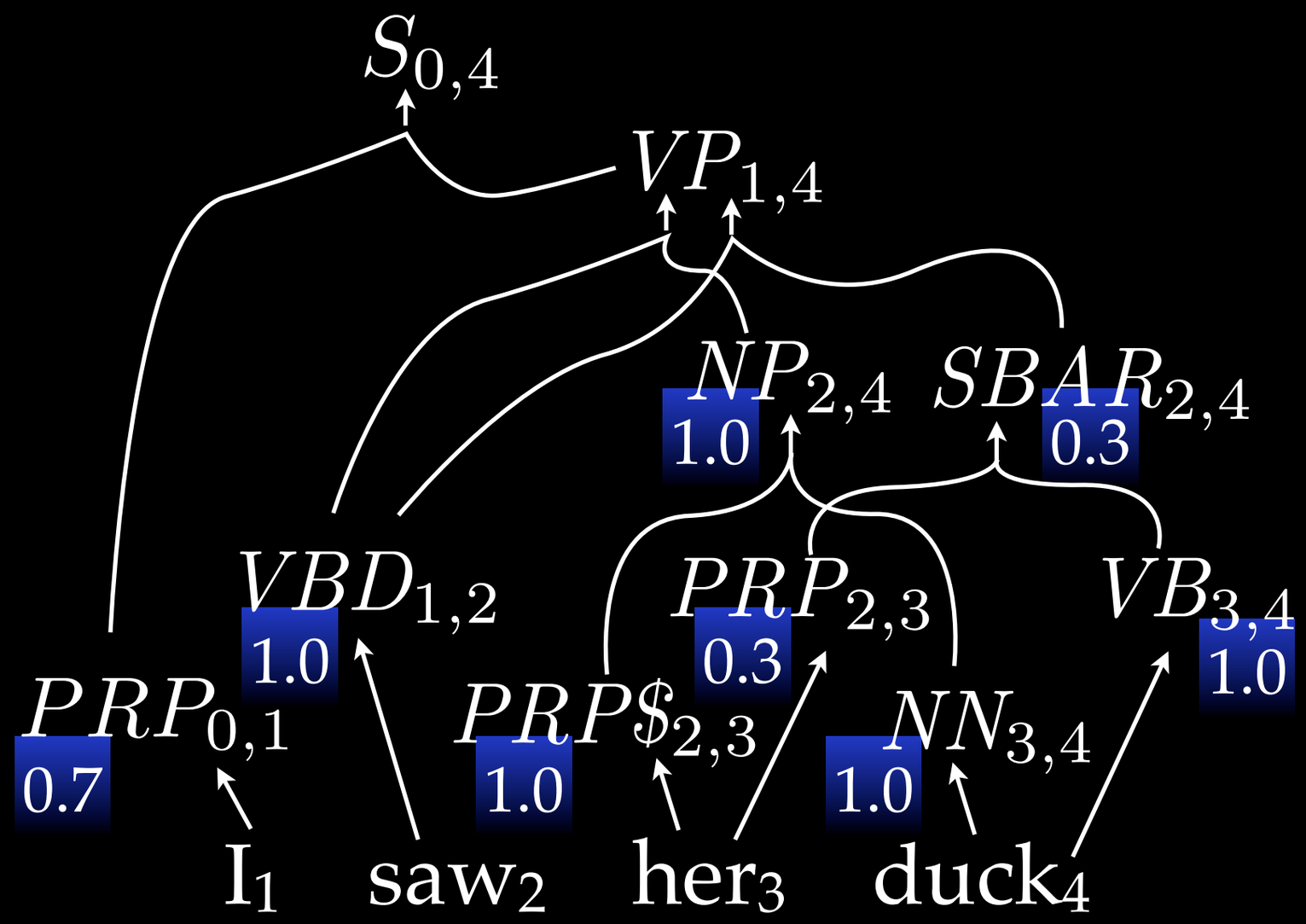
VP → VBD SBAR (0.2)

VBD → saw (1.0)



Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



Probabilistic Parsing

NN → duck (1.0)

NP → PRP$ NN (1.0)

PRP → her (0.3)

PRP → I (0.7)

PRP$ → her (1.0)

S → PRP VP (1.0)

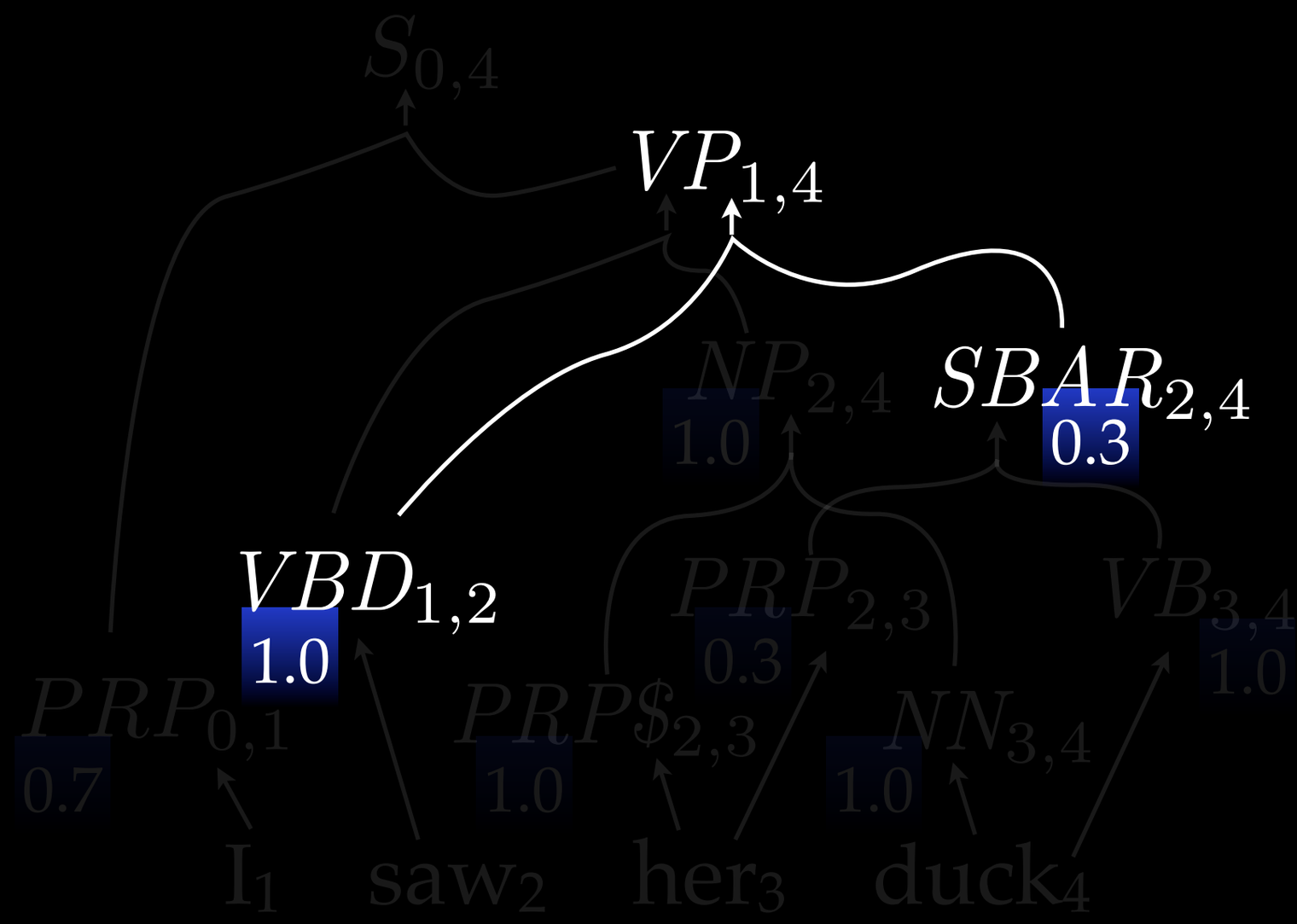
SBAR → PRP VB (1.0)

VB → duck (1.0)

VP → VBD NP (0.8)

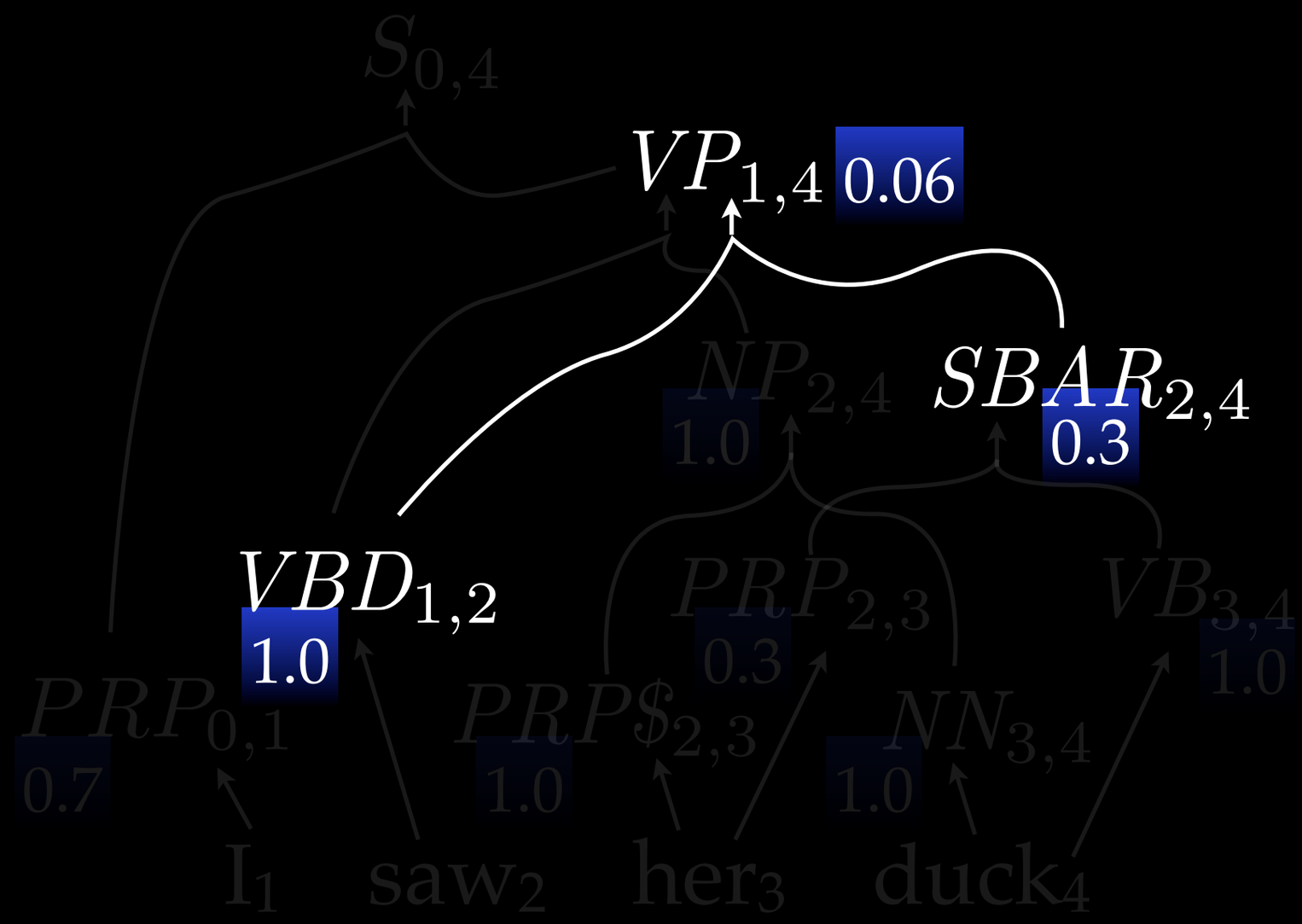
VP → VBD SBAR (0.2)

VBD → saw (1.0)



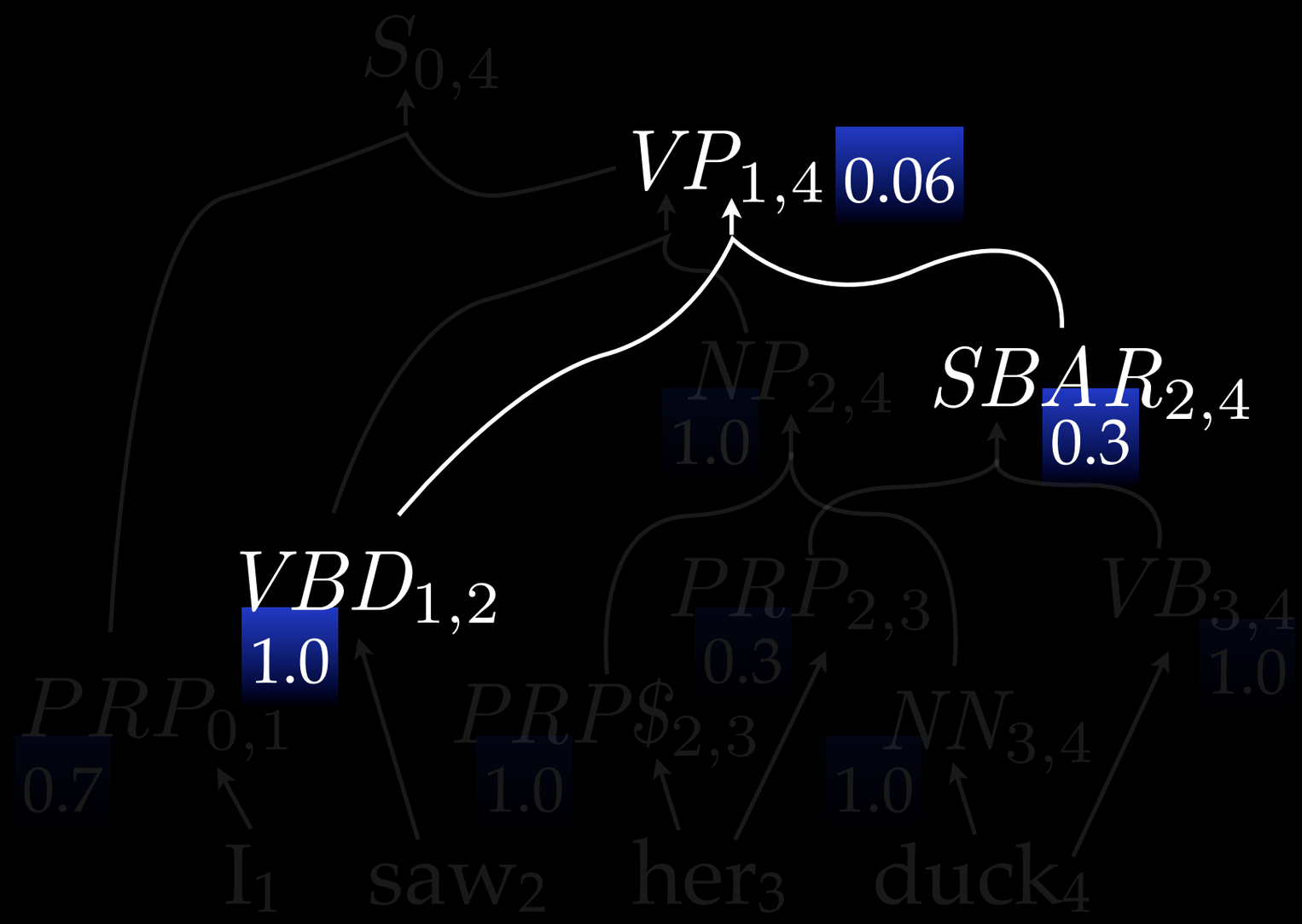
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



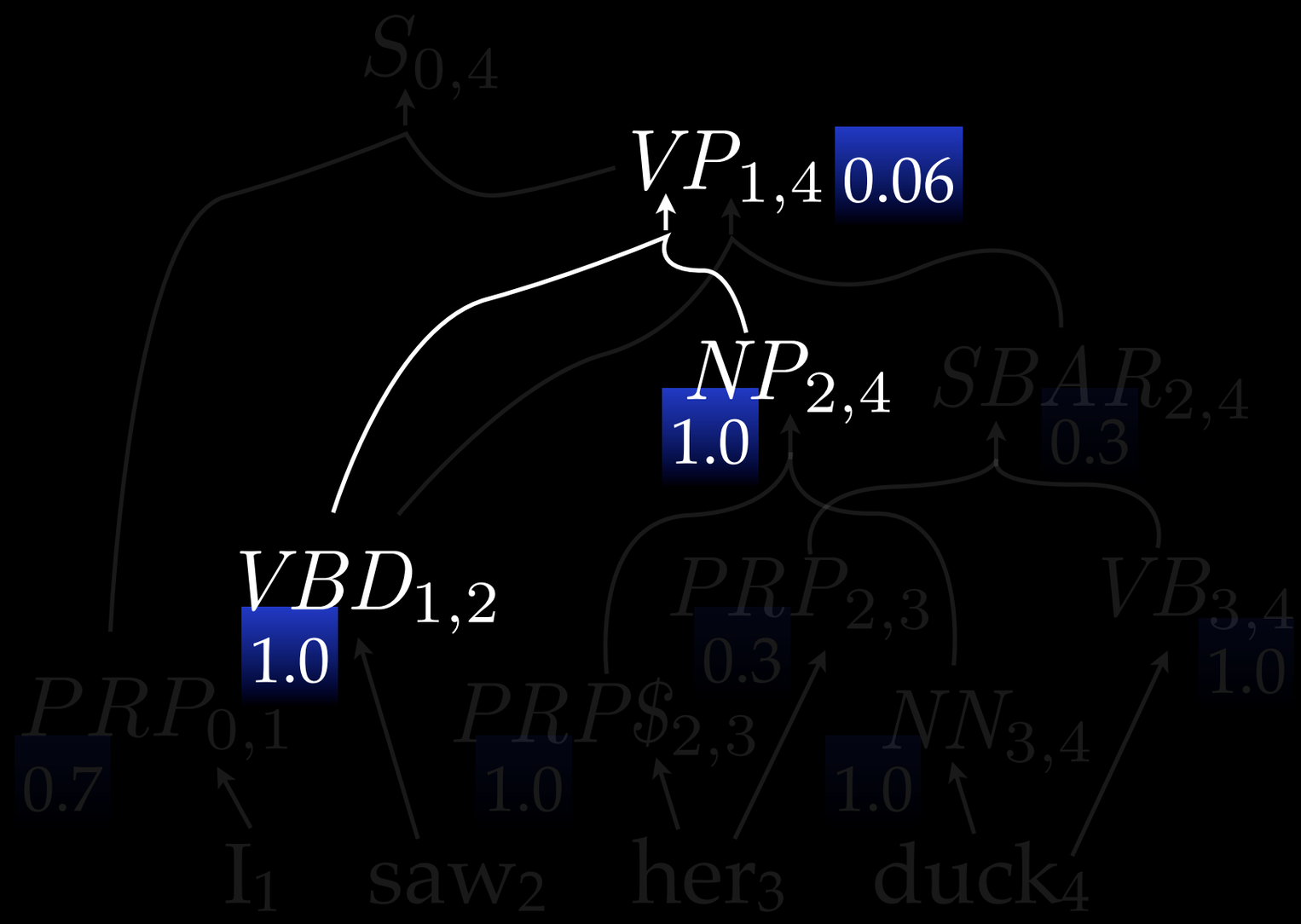
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



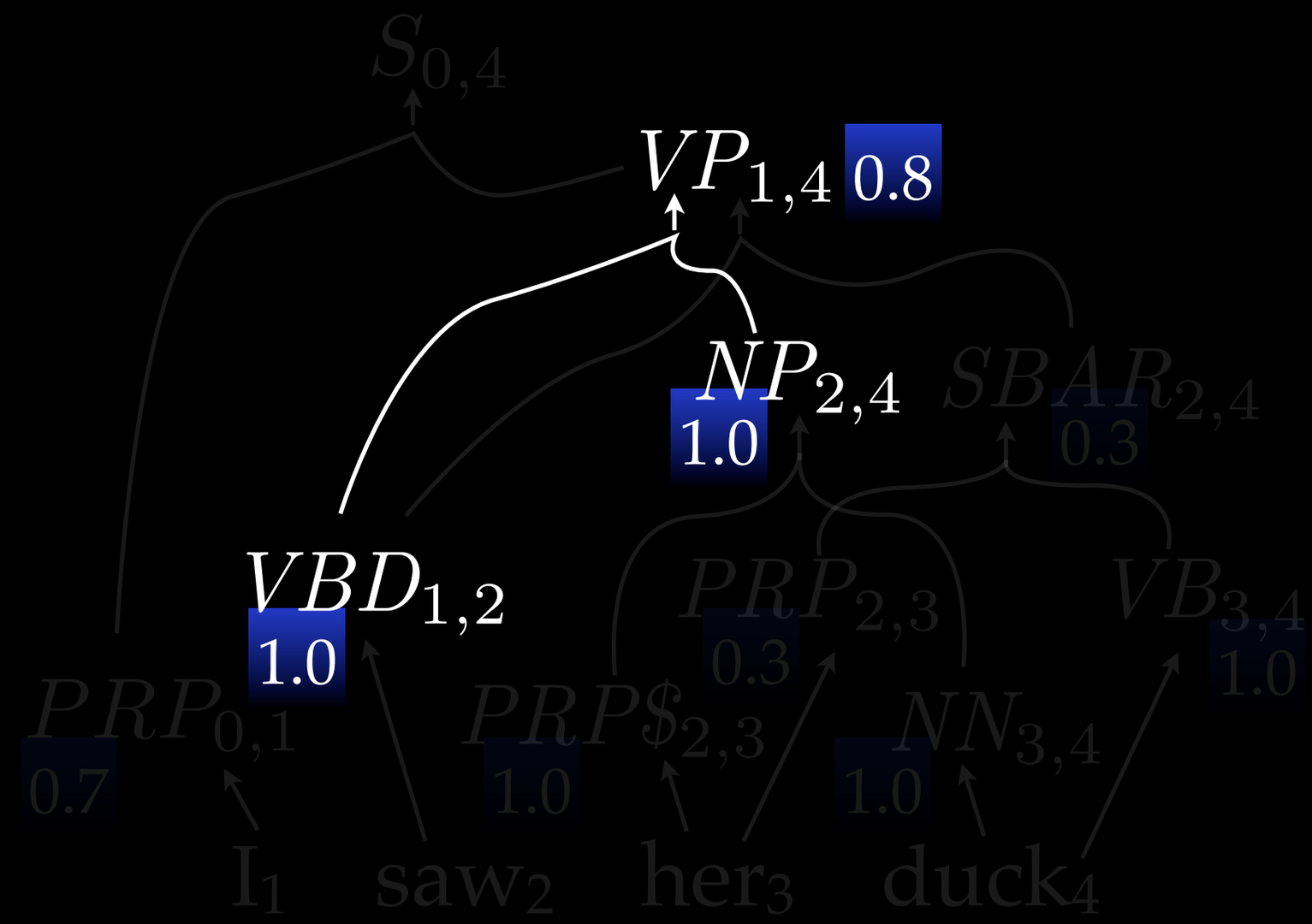
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



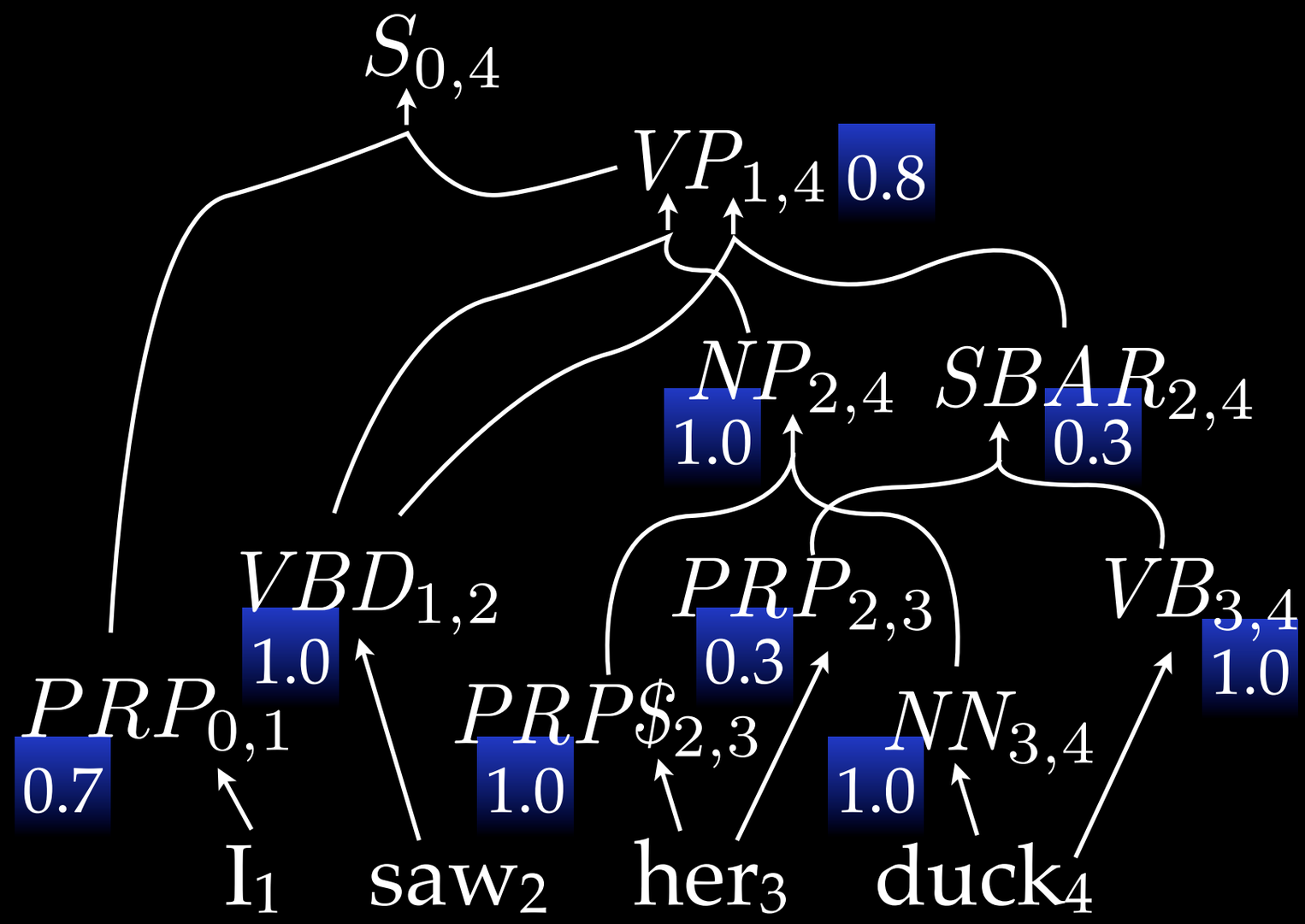
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



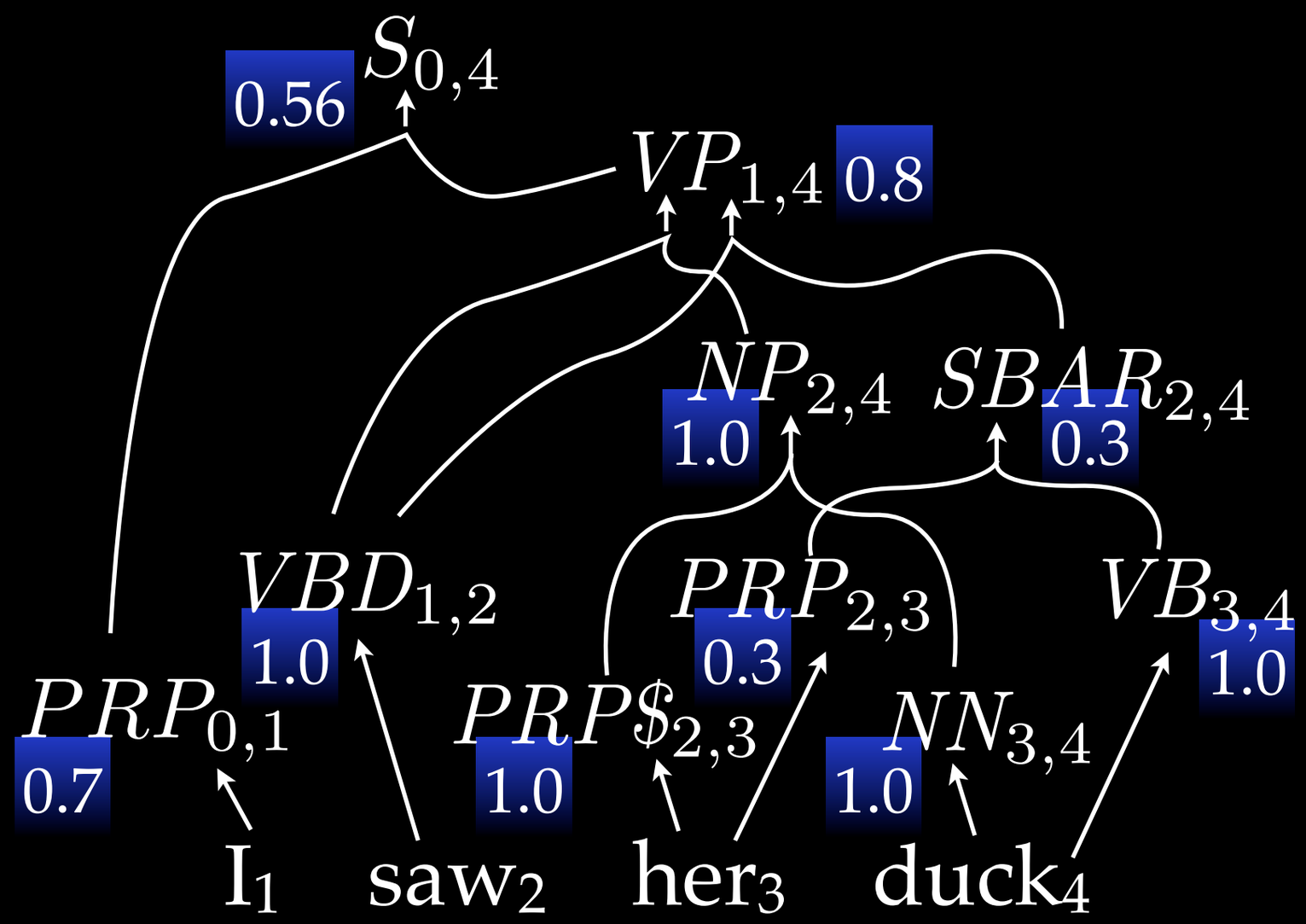
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



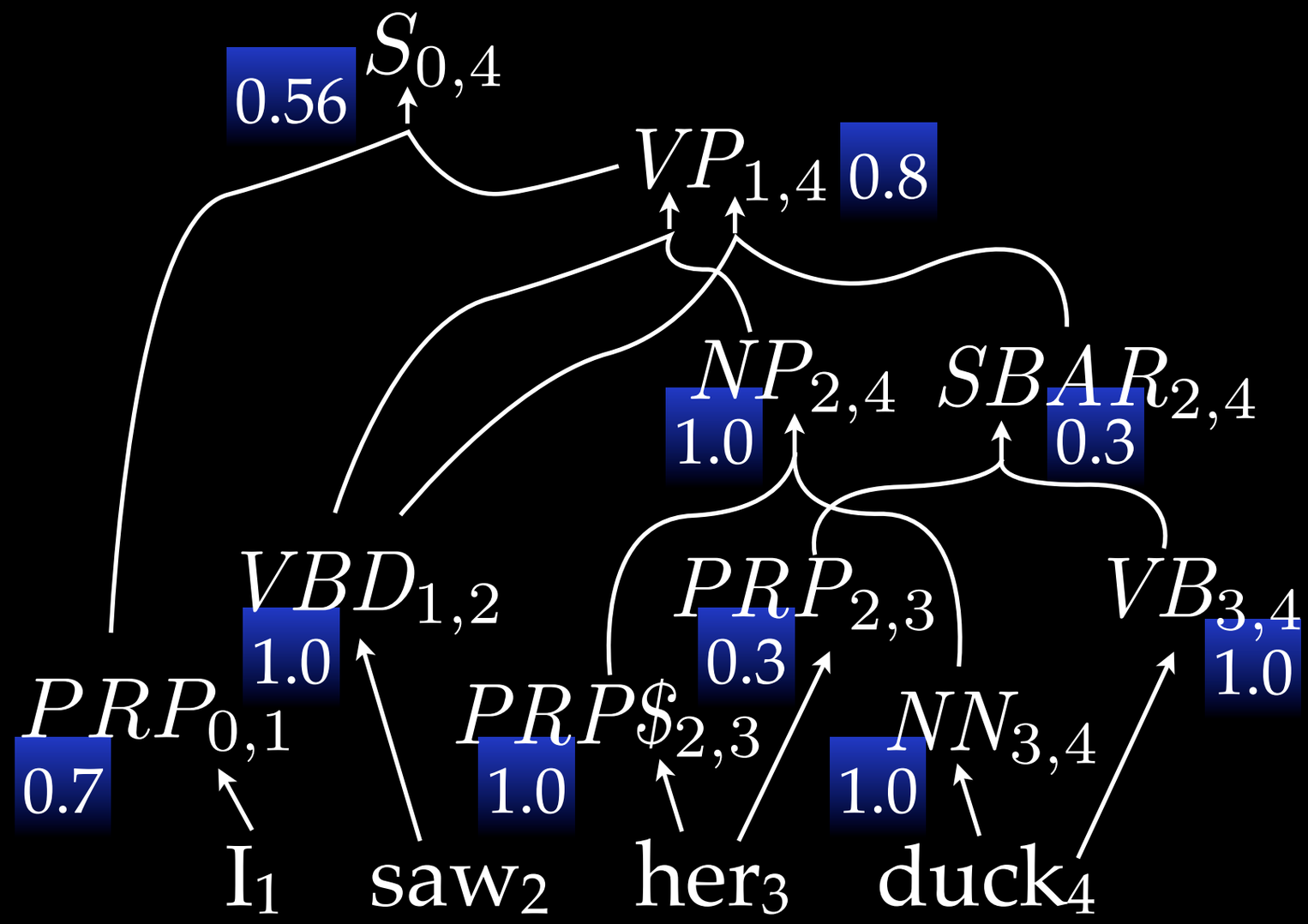
Probabilistic Parsing

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



Probabilistic Parsing

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \rightarrow YZ))$$



Computing Expectations

NN → duck (1.0)

NP → PRP$ NN (1.0)

PRP → her (0.3)

PRP → I (0.7)

PRP$ → her (1.0)

S → PRP VP (1.0)

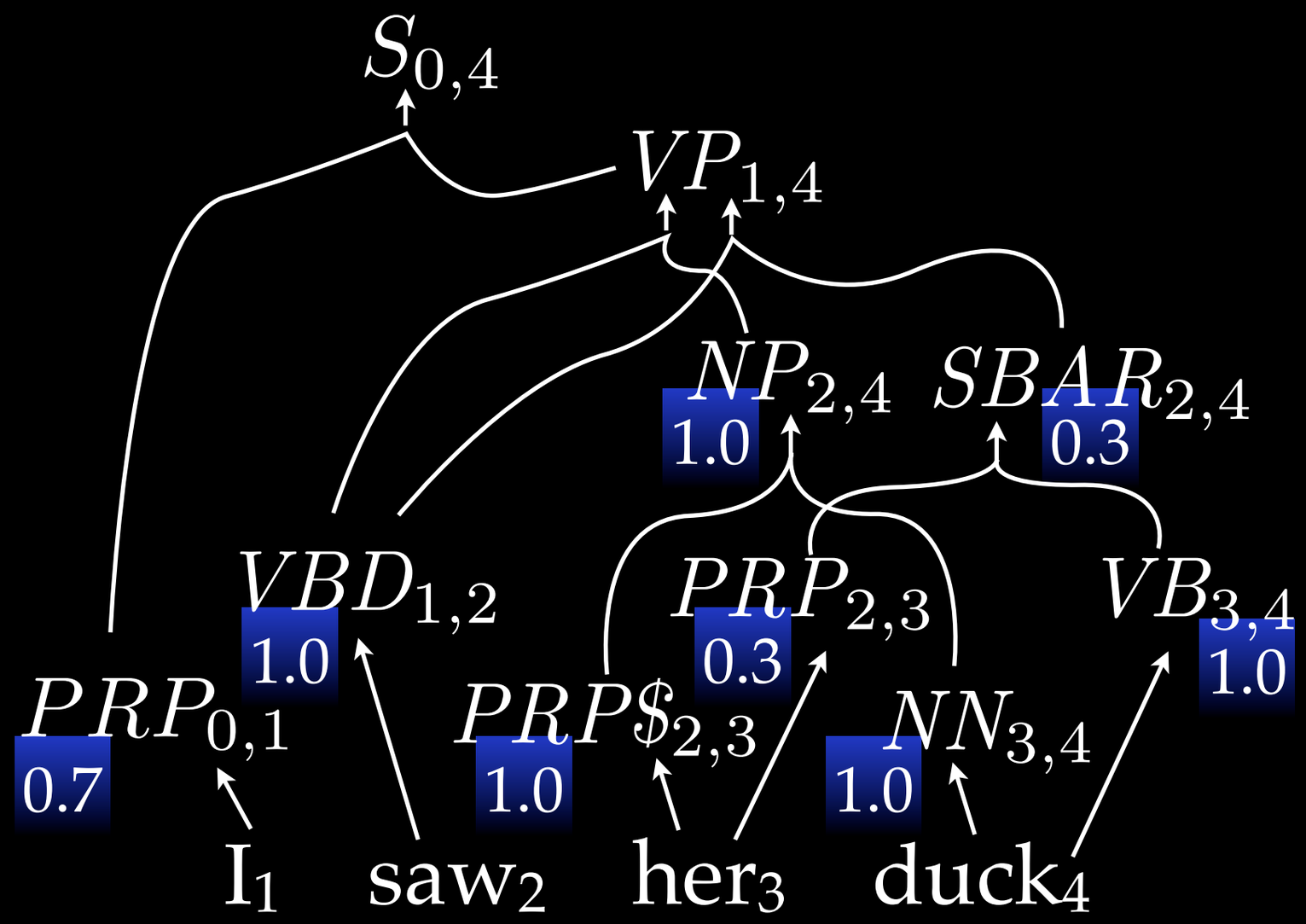
SBAR → PRP VB (1.0)

VB → duck (1.0)

VP → VBD NP (0.8)

VP → VBD SBAR (0.2)

VBD → saw (1.0)



Computing Expectations

NN → duck (1.0)

NP → PRP$ NN (1.0)

PRP → her (0.3)

PRP → I (0.7)

PRP$ → her (1.0)

S → PRP VP (1.0)

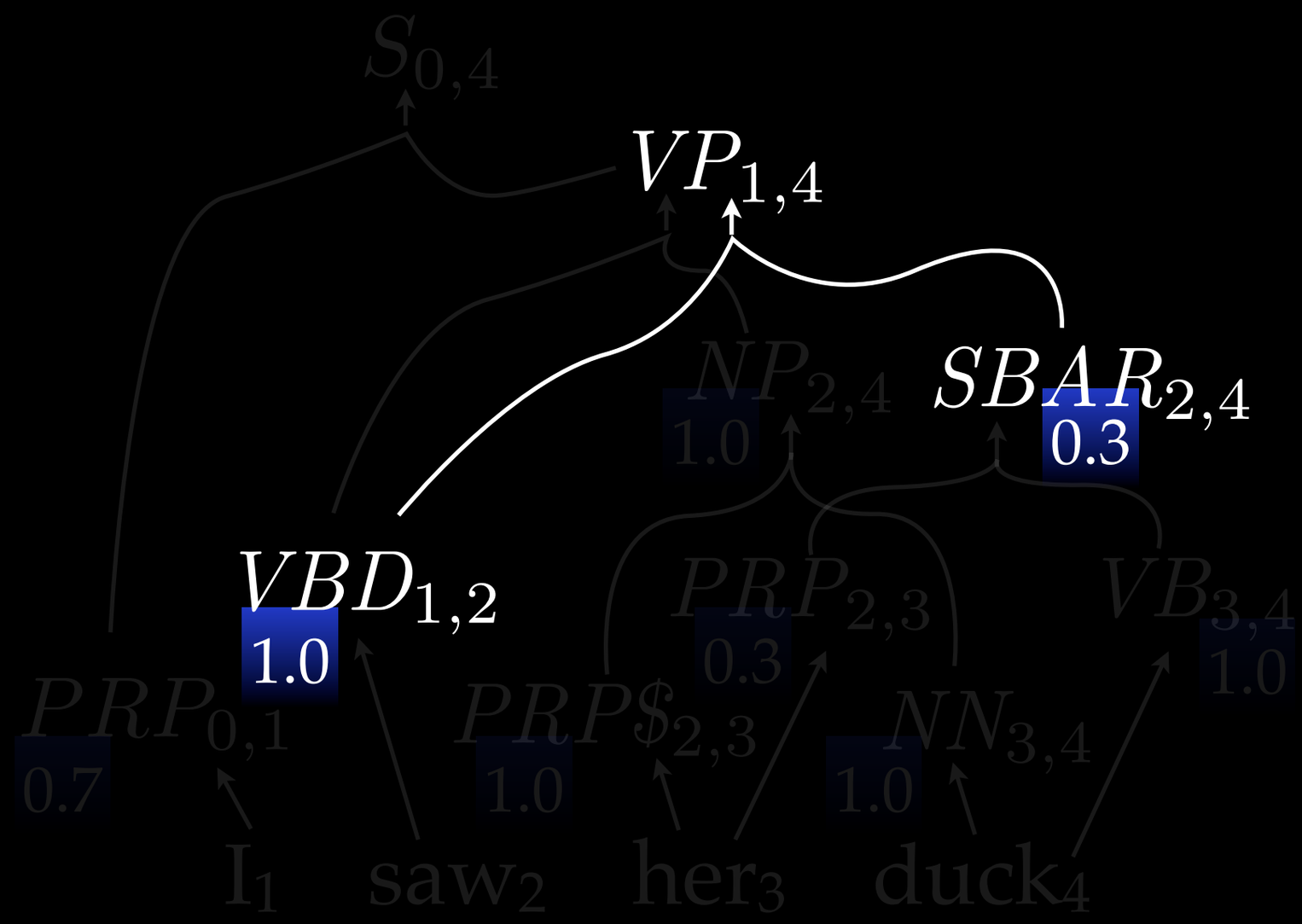
SBAR → PRP VB (1.0)

VB → duck (1.0)

VP → VBD NP (0.8)

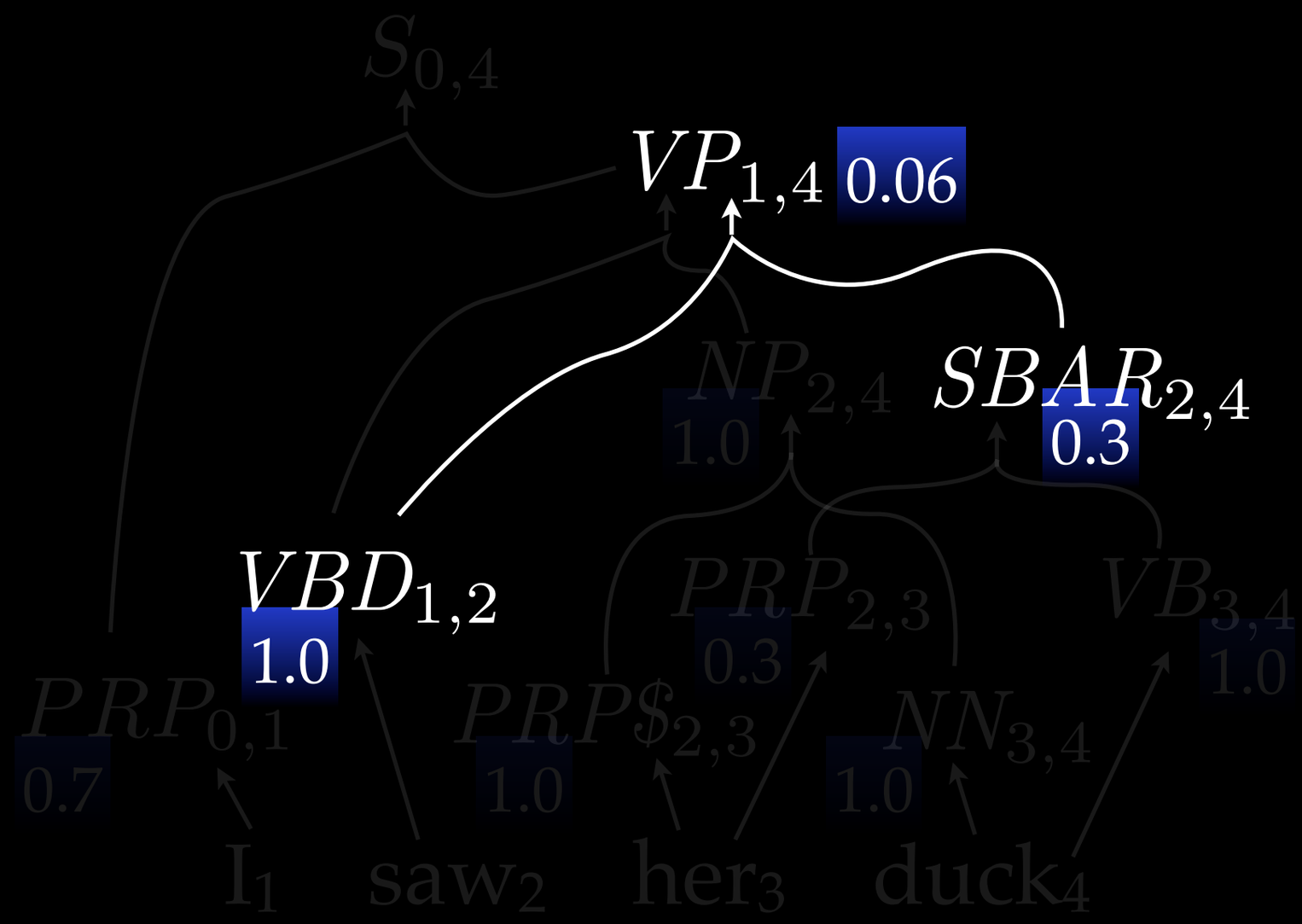
VP → VBD SBAR (0.2)

VBD → saw (1.0)



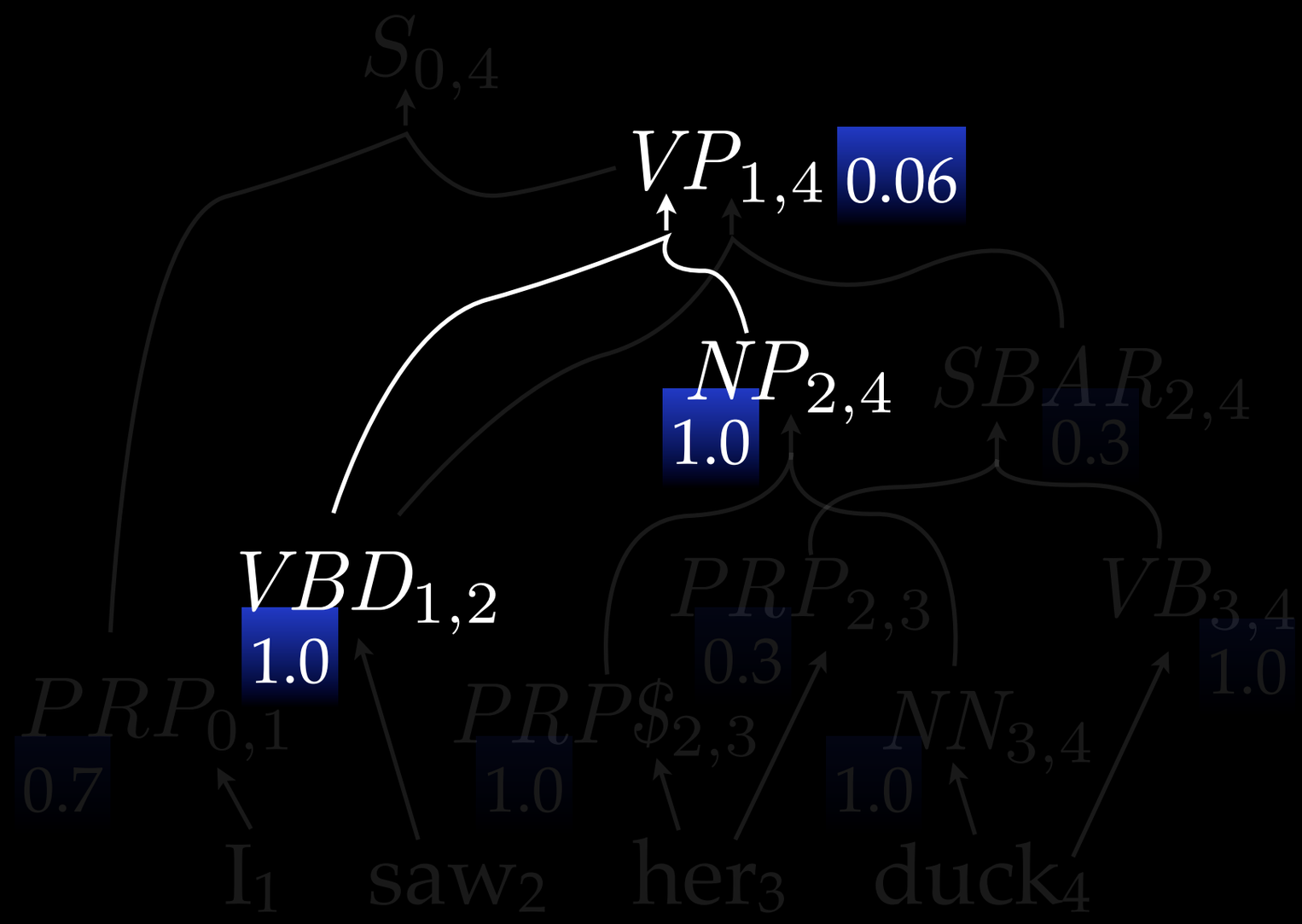
Computing Expectations

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



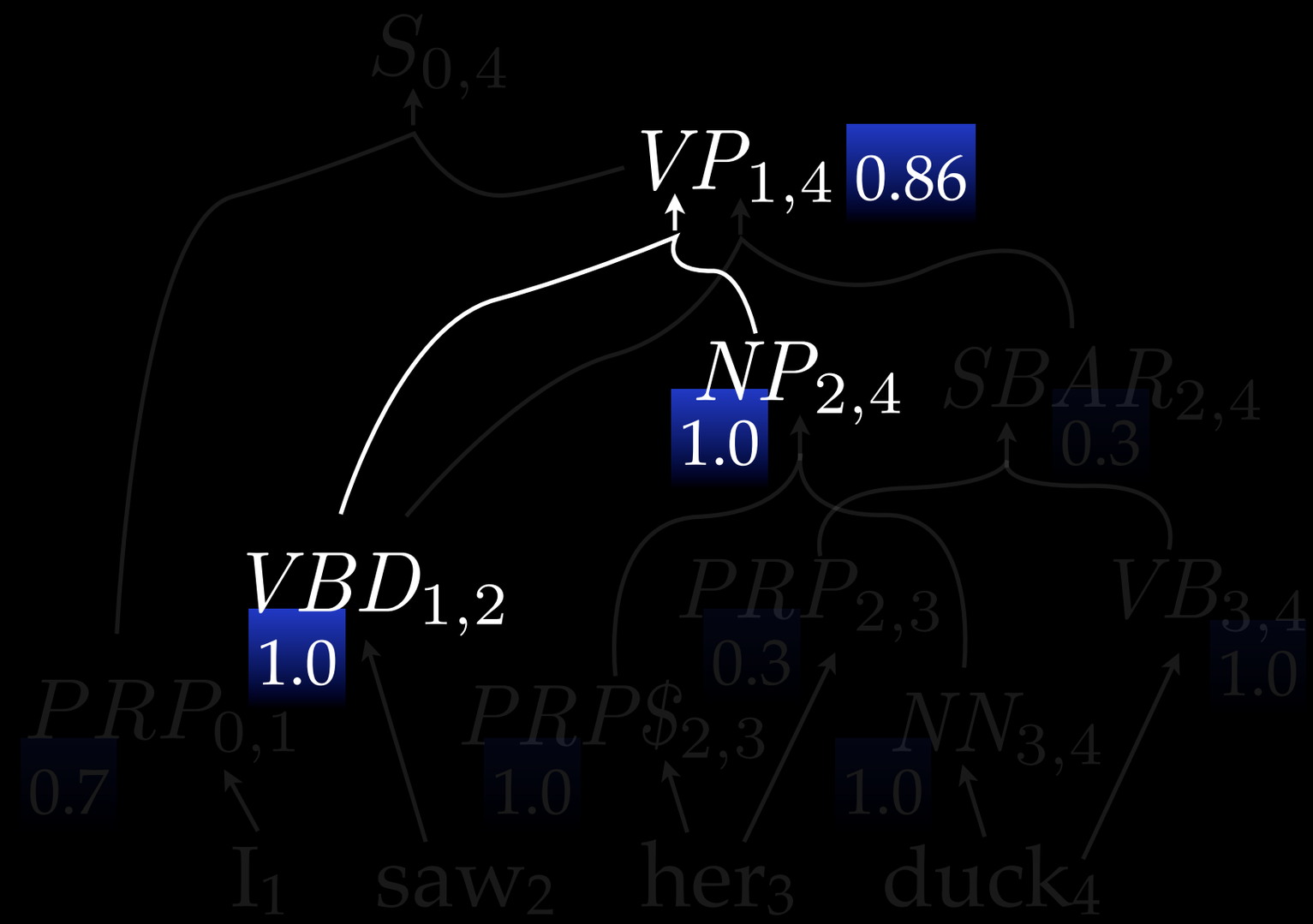
Computing Expectations

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



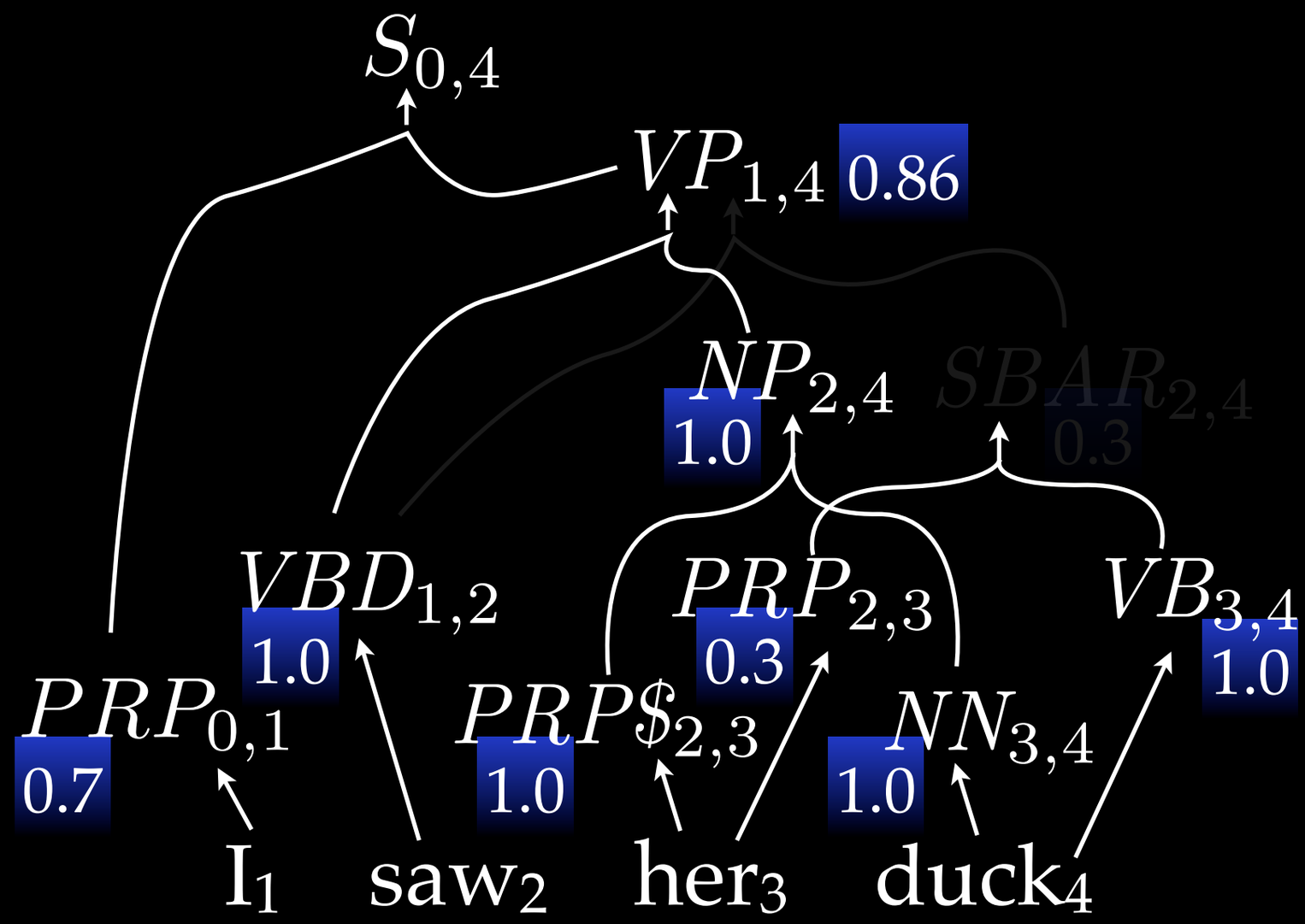
Computing Expectations

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



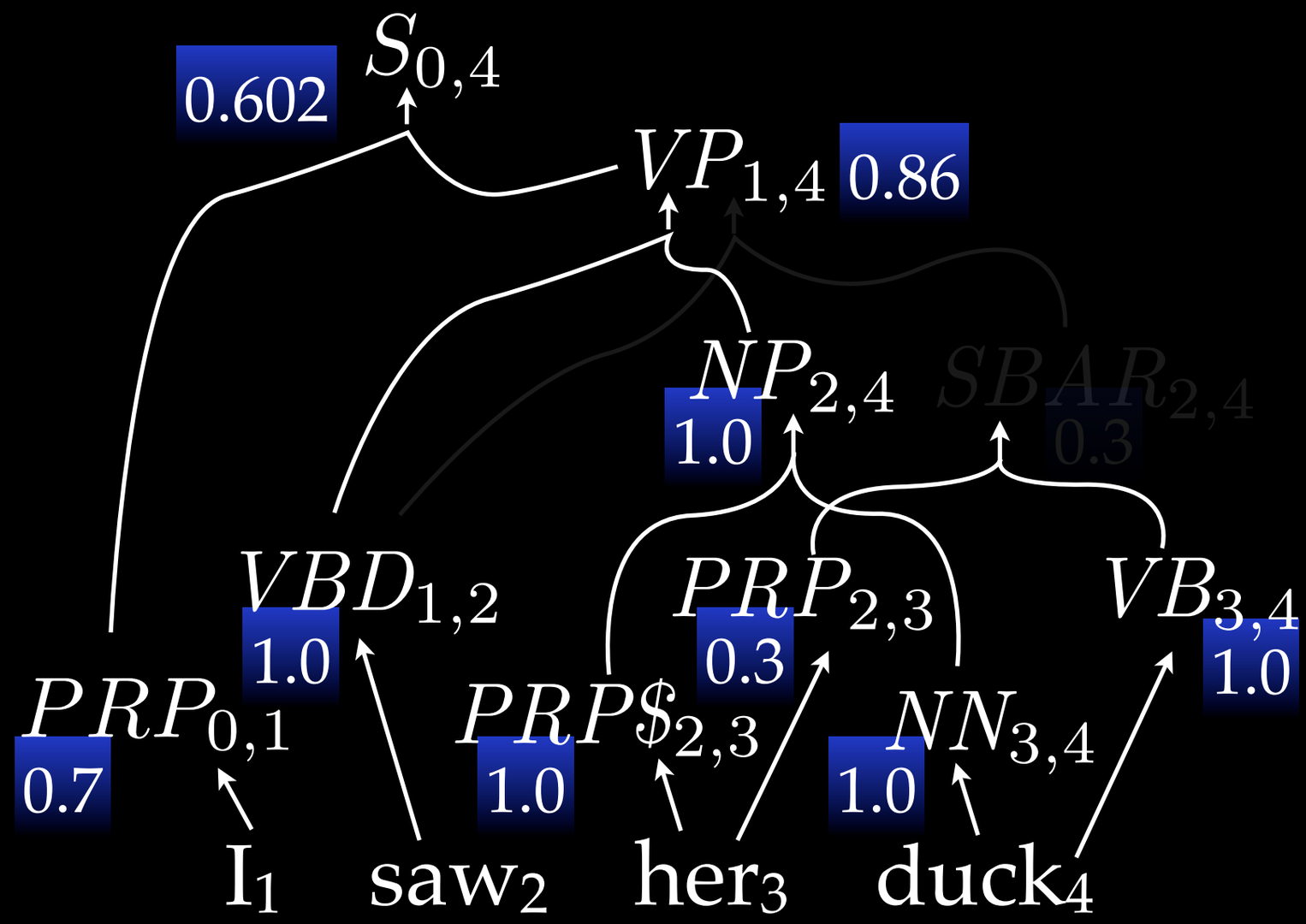
Computing Expectations

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



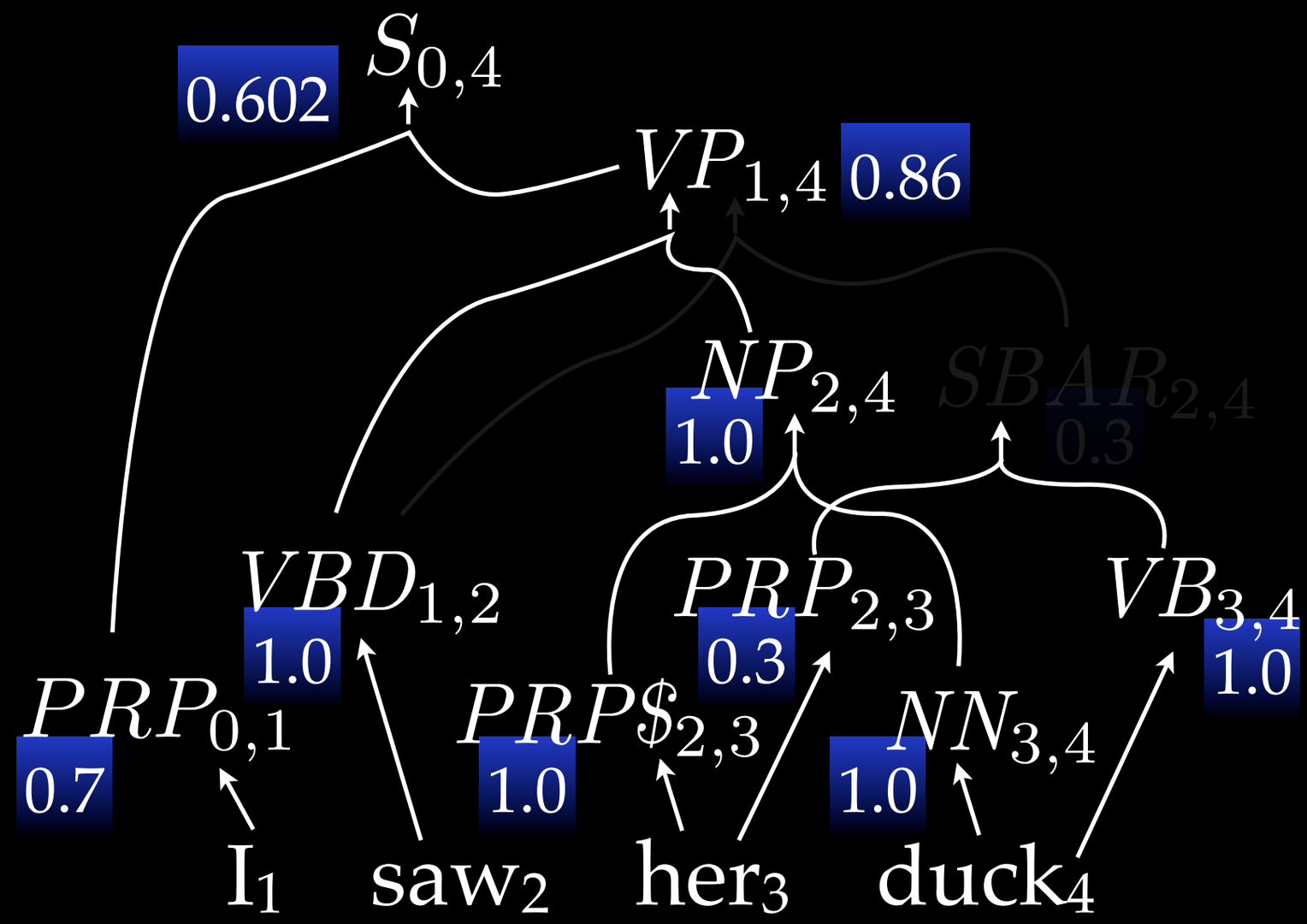
Computing Expectations

NN → duck	(1.0)
NP → PRP$ NN	(1.0)
PRP → her	(0.3)
PRP → I	(0.7)
PRP$ → her	(1.0)
S → PRP VP	(1.0)
SBAR → PRP VB	(1.0)
VB → duck	(1.0)
VP → VBD NP	(0.8)
VP → VBD SBAR	(0.2)
VBD → saw	(1.0)



Computing Expectations

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \rightarrow YZ))$$



Semiring Parsing

$$X_{i,j} \leftarrow Y_{i,k} \wedge Z_{k,j} \wedge (X \rightarrow YZ)$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \rightarrow YZ))$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \rightarrow YZ))$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to YZ))$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to YZ))$$

$$\langle \{T, F\}, \vee, \wedge \rangle$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to YZ))$$

$$\langle \{T, F\}, \vee, \wedge \rangle$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$\langle \mathbb{R}, \max, \times \rangle$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to YZ))$$

$$\langle \{T, F\}, \vee, \wedge \rangle$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$\langle \mathbb{R}, \max, \times \rangle$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$\langle \mathbb{R}, +, \times \rangle$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to YZ))$$

$$\langle \{T, F\}, \vee, \wedge \rangle$$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$\langle \mathbb{R}, \max, \times \rangle$$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to YZ))$$

$$\langle \mathbb{R}, +, \times \rangle$$

$$X_{i,j} = X_{i,j} \oplus (Y_{i,k} \otimes Z_{k,j} \otimes R(X \to YZ))$$

Semiring Parsing

$$X_{i,j} = X_{i,j} \vee (Y_{i,k} \wedge Z_{k,j} \wedge (X \to Y\,Z))$$

boolean $\quad \langle \{T, F\}, \vee, \wedge \rangle$

$$X_{i,j} = \max(X_{i,j}, Y_{i,k} \times Z_{k,j} \times p(X \to Y\,Z))$$

Viterbi $\quad \langle \mathbb{R}, \max, \times \rangle$

$$X_{i,j} = X_{i,j} + (Y_{i,k} \times Z_{k,j} \times p(X \to Y\,Z))$$

inside $\quad \langle \mathbb{R}, +, \times \rangle$

$$X_{i,j} = X_{i,j} \oplus (Y_{i,k} \otimes Z_{k,j} \otimes R(X \to Y\,Z))$$

Parsing

Is Intersection!

$NN_{3,4} \rightarrow$ duck

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ her

$PRP_{0,1} \rightarrow$ I

$PRP\$_{2,3} \rightarrow$ her

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

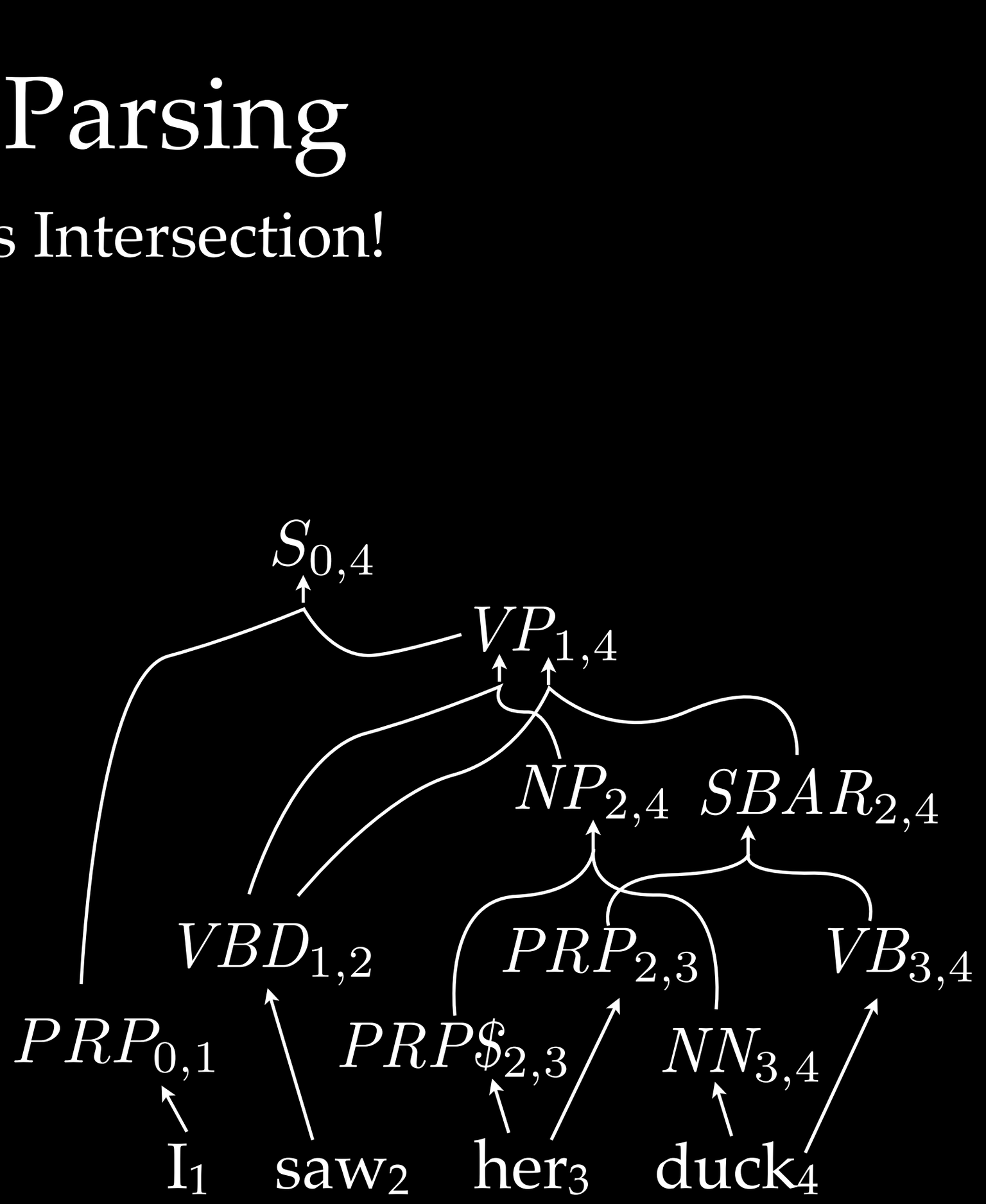
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ duck

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

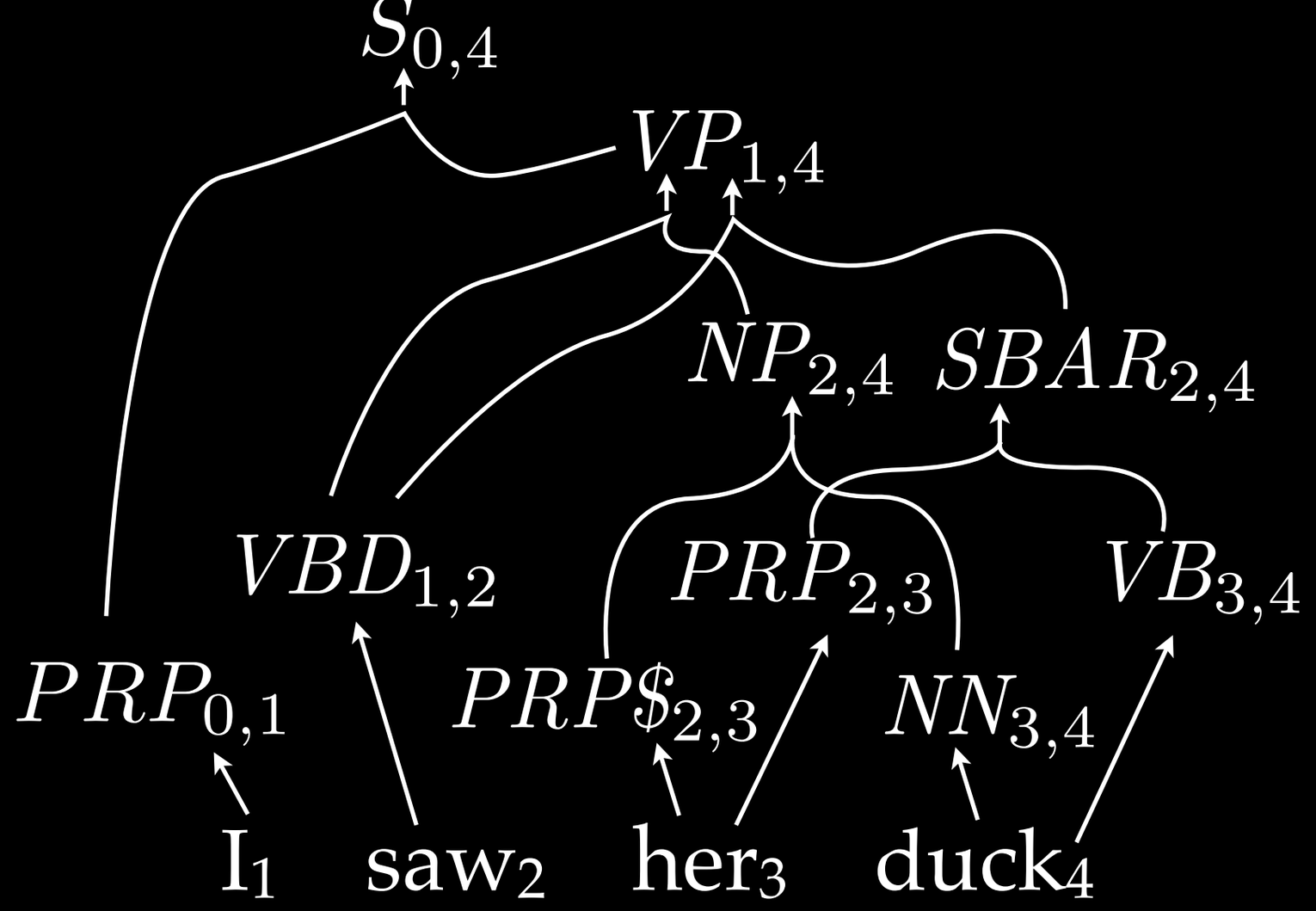
$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ saw



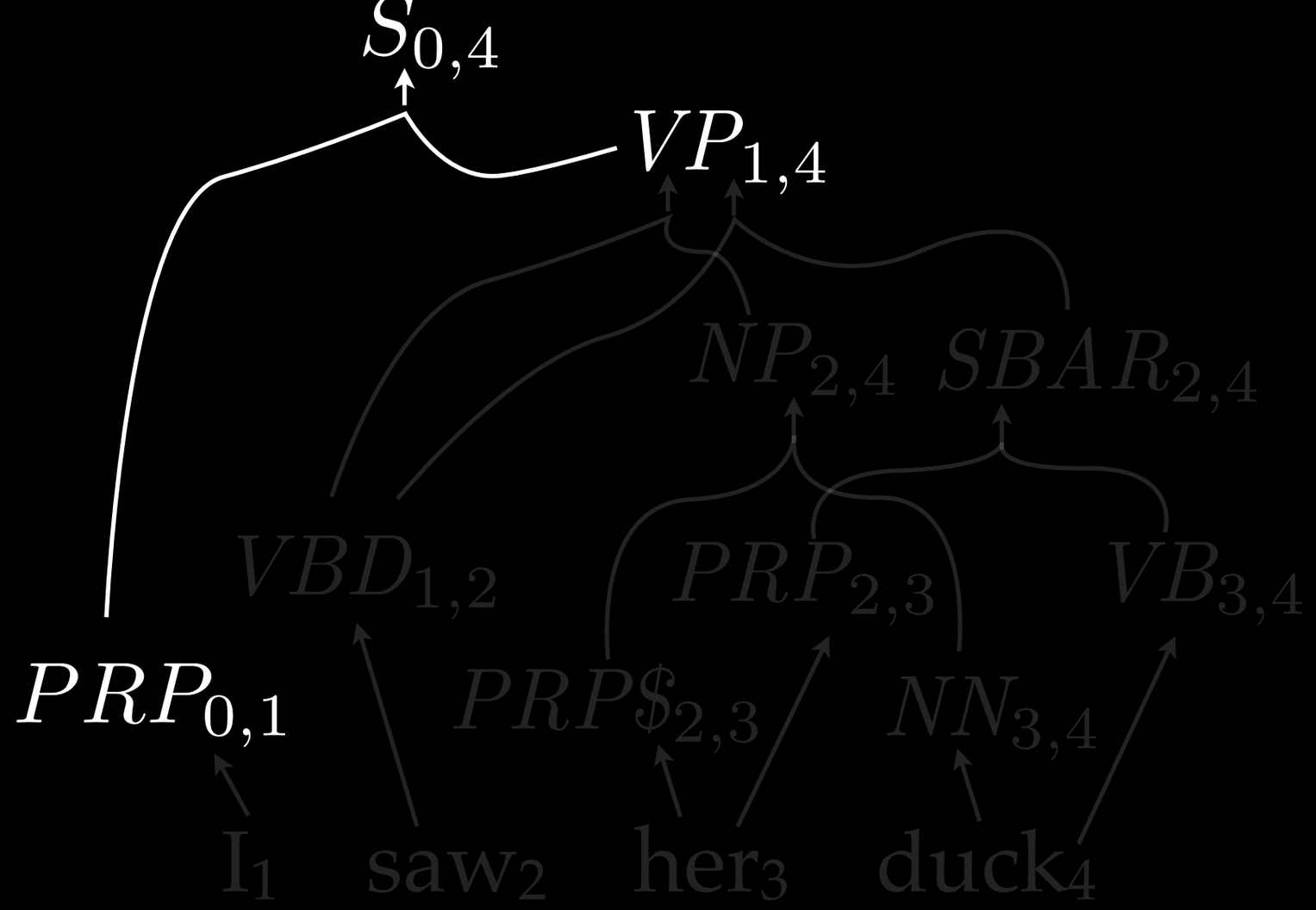
Parsing

Is Intersection!



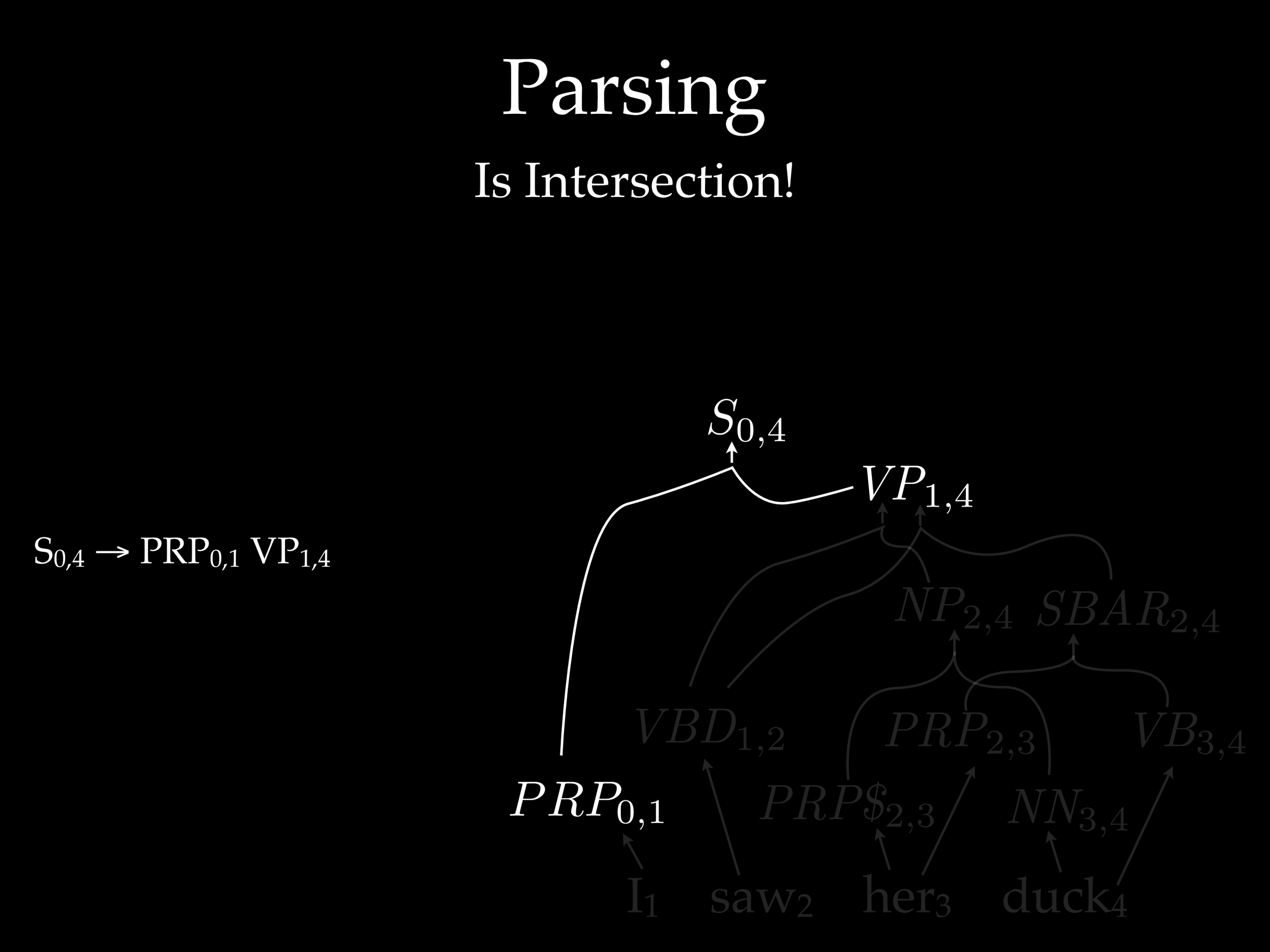
Parsing

Is Intersection!



Parsing

Is Intersection!



$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

Parsing

Is Intersection!

$S_{0,4}$

$VP_{1,4}$

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$NP_{2,4}$ $SBAR_{2,4}$

$VBD_{1,2}$ $PRP_{2,3}$ $VB_{3,4}$

$PRP_{0,1}$ $PRP\$_{2,3}$ $NN_{3,4}$

I_1 saw_2 her_3 $duck_4$

Parsing

Is Intersection!

$NN_{3,4} \rightarrow$ duck

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ her

$PRP_{0,1} \rightarrow$ I

$PRP\$_{2,3} \rightarrow$ her

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

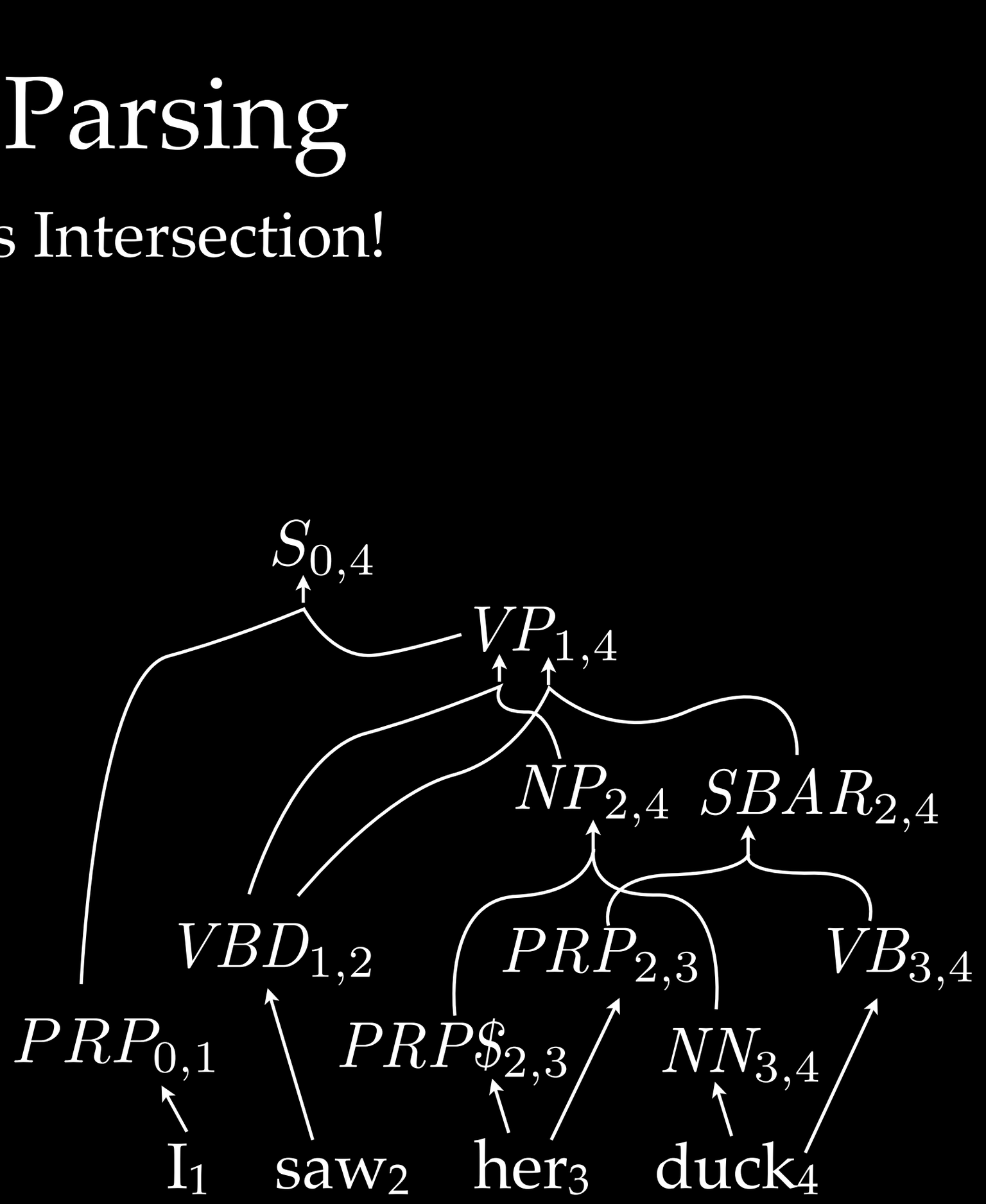
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ duck

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ saw



Parsing

Is Intersection!

$NN_{3,4} \rightarrow$ duck	$NN_{3,4} \rightarrow$ pato
$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$	$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$
$PRP_{2,3} \rightarrow$ her	$PRP_{2,3} \rightarrow$ su
$PRP_{0,1} \rightarrow$ I	$PRP_{0,1} \rightarrow$ yo
$PRP\$_{2,3} \rightarrow$ her	$PRP\$_{2,3} \rightarrow$ ella
$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$	$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$	$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$
$VB_{3,4} \rightarrow$ duck	$VB_{3,4} \rightarrow$ agacharse
$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$	$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$
$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$	$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$
$VBD_{1,2} \rightarrow$ saw	$VBD_{1,2} \rightarrow$ vi

Parsing

Is Intersection!

$NN_{3,4} \rightarrow$ duck

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ her

$PRP_{0,1} \rightarrow$ I

$PRP\$_{2,3} \rightarrow$ her

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ duck

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ saw

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi

yo vi ella agacharse

yo vi su pato

Synchronous Parsing as Intersection

Synchronous Parsing as Intersection

- Parse the English sentence (intersection).

Synchronous Parsing as Intersection

- Parse the English sentence (intersection).
- Project grammar into French.

Synchronous Parsing as Intersection

- Parse the English sentence (intersection).
- Project grammar into French.
- Parse the French sentence (intersection).

Synchronous Parsing as Intersection

- Parse the English sentence (intersection).
- Project grammar into French.
- Parse the French sentence (intersection).

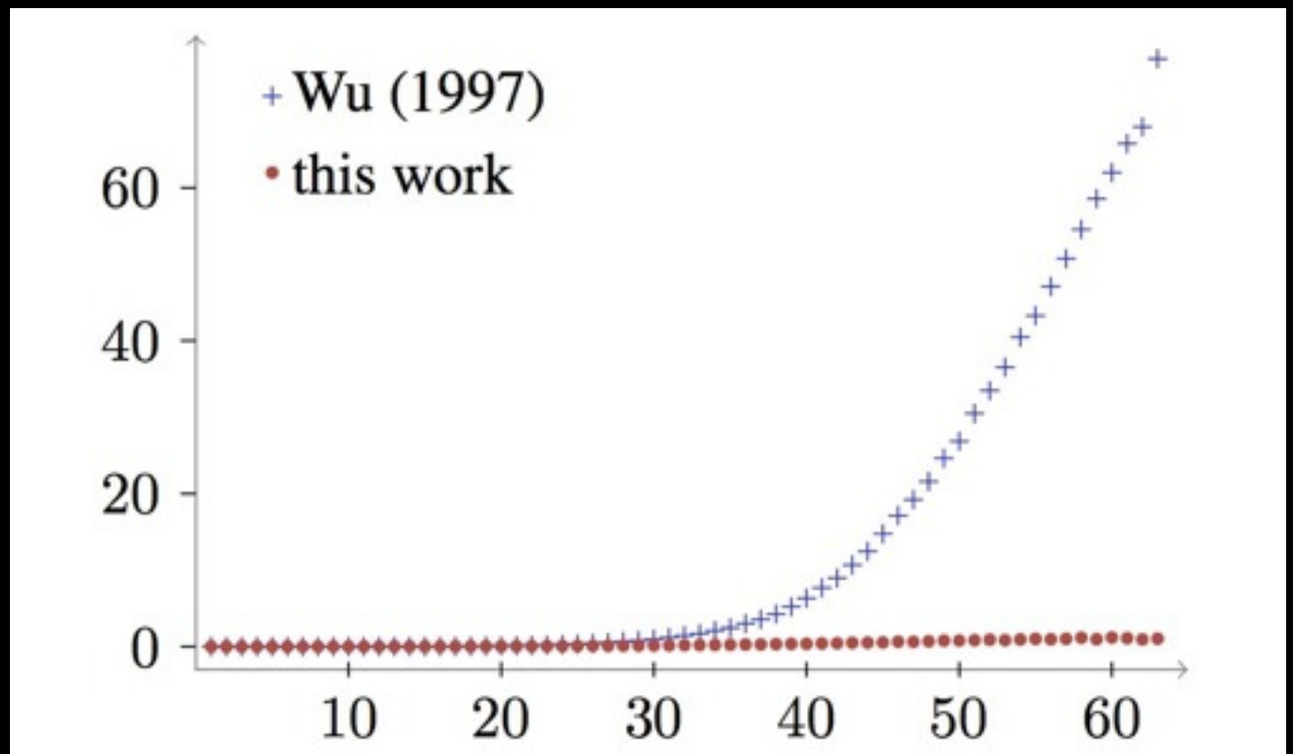


Figure 3: Average synchronous parser run-time (in seconds) as a function of Arabic sentence length (in words).

Dyer, NAACL 2010

Translation as Intersection?

$NN_{3,4}$ → duck

$NP_{2,4}$ → $PRP\$_{2,3}$ $NN_{3,4}$

$PRP_{2,3}$ → her

$PRP_{0,1}$ → I

$PRP\$_{2,3}$ → her

$S_{0,4}$ → $PRP_{0,1}$ $VP_{1,4}$

$SBAR_{2,4}$ → $PRP_{2,3}$ $VB_{3,4}$

$VB_{3,4}$ → duck

$VP_{1,4}$ → $VBD_{1,2}$ $NP_{2,4}$

$VP_{1,4}$ → $VBD_{1,2}$ $SBAR_{2,4}$

$VBD_{1,2}$ → saw

$NN_{3,4}$ → pato

$NP_{2,4}$ → $PRP\$_{2,3}$ $NN_{3,4}$

$PRP_{2,3}$ → su

$PRP_{0,1}$ → yo

$PRP\$_{2,3}$ → ella

$S_{0,4}$ → $PRP_{0,1}$ $VP_{1,4}$

$SBAR_{2,4}$ → $PRP_{2,3}$ $VB_{3,4}$

$VB_{3,4}$ → agacharse

$VP_{1,4}$ → $VBD_{1,2}$ $NP_{2,4}$

$VP_{1,4}$ → $VBD_{1,2}$ $SBAR_{2,4}$

$VBD_{1,2}$ → vi

yo vi ella agacharse

yo vi su pato

Translation as Intersection?

Observation: target grammar generates a *finite language*

$NN_{3,4}$ → duck	$NN_{3,4}$ → pato
$NP_{2,4}$ → $PRP\$_{2,3}$ $NN_{3,4}$	$NP_{2,4}$ → $PRP\$_{2,3}$ $NN_{3,4}$
$PRP_{2,3}$ → her	$PRP_{2,3}$ → su
$PRP_{0,1}$ → I	$PRP_{0,1}$ → yo
$PRP\$_{2,3}$ → her	$PRP\$_{2,3}$ → ella
$S_{0,4}$ → $PRP_{0,1}$ $VP_{1,4}$	$S_{0,4}$ → $PRP_{0,1}$ $VP_{1,4}$
$SBAR_{2,4}$ → $PRP_{2,3}$ $VB_{3,4}$	$SBAR_{2,4}$ → $PRP_{2,3}$ $VB_{3,4}$
$VB_{3,4}$ → duck	$VB_{3,4}$ → agacharse
$VP_{1,4}$ → $VBD_{1,2}$ $NP_{2,4}$	$VP_{1,4}$ → $VBD_{1,2}$ $NP_{2,4}$
$VP_{1,4}$ → $VBD_{1,2}$ $SBAR_{2,4}$	$VP_{1,4}$ → $VBD_{1,2}$ $SBAR_{2,4}$
$VBD_{1,2}$ → saw	$VBD_{1,2}$ → vi

yo vi ella agacharse

yo vi su pato

Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi

Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi

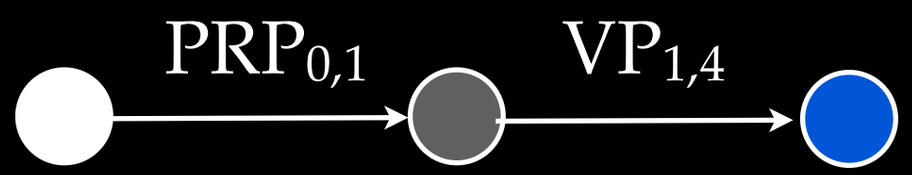
Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo



$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi

Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

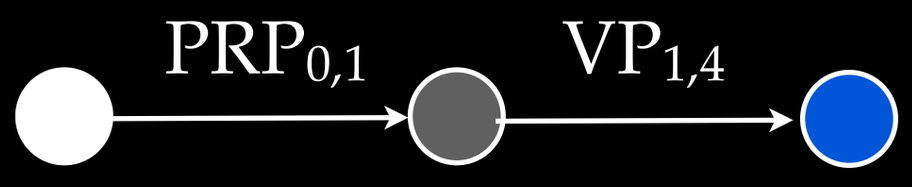
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

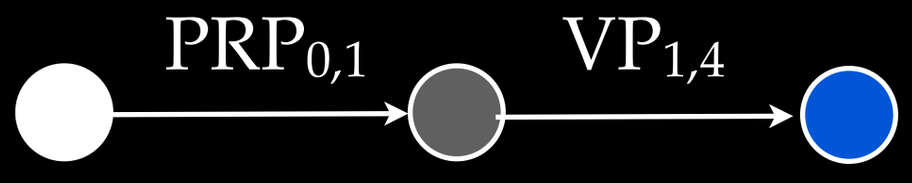
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

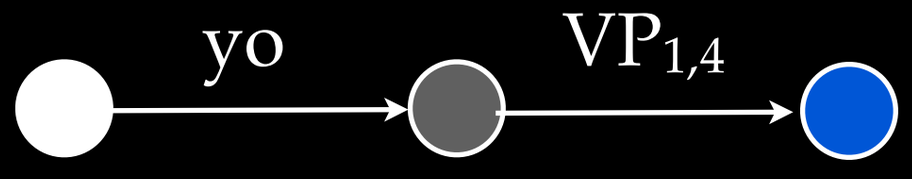
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

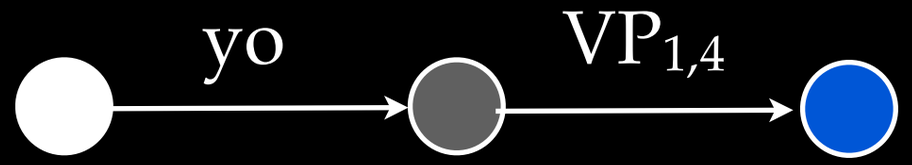
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



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$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

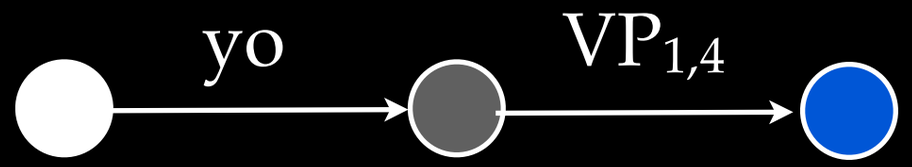
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



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$PRP_{2,3} \rightarrow$ su

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$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

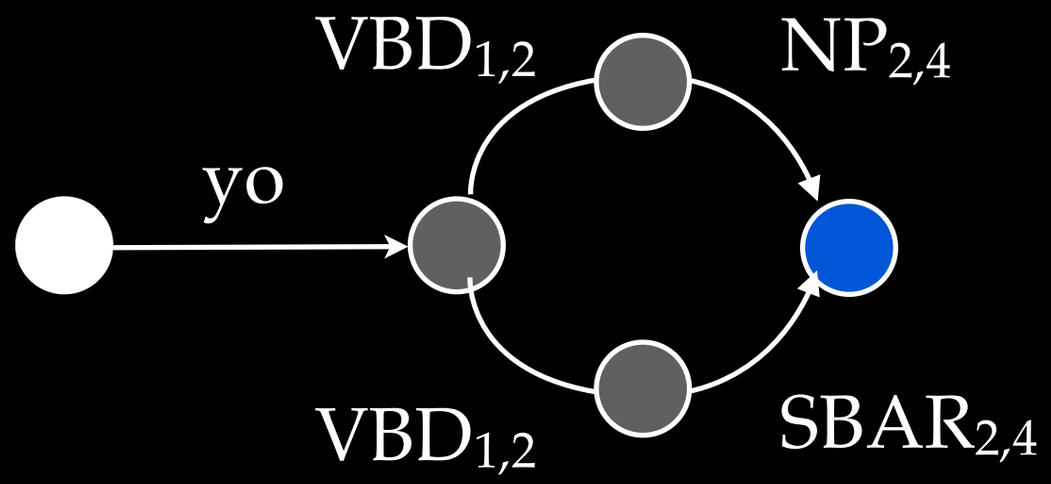
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



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$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

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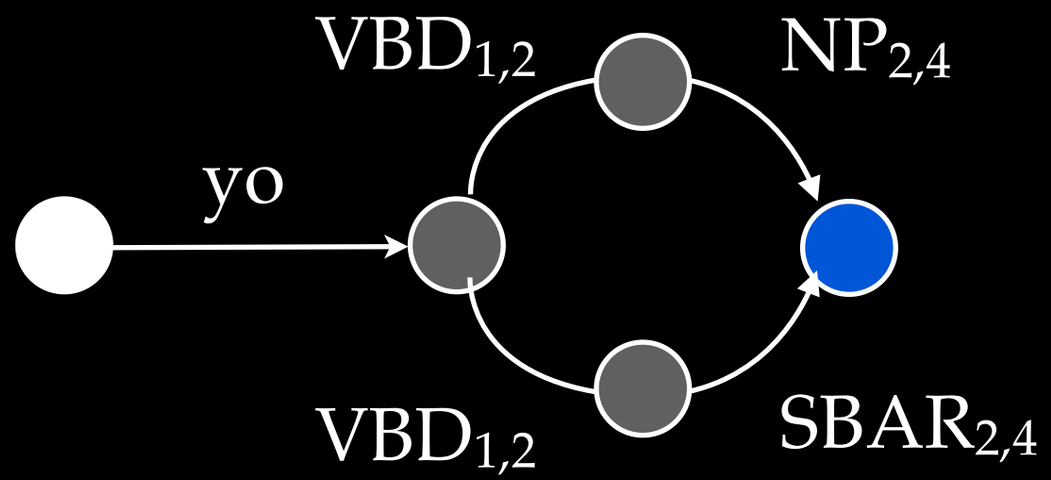
$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



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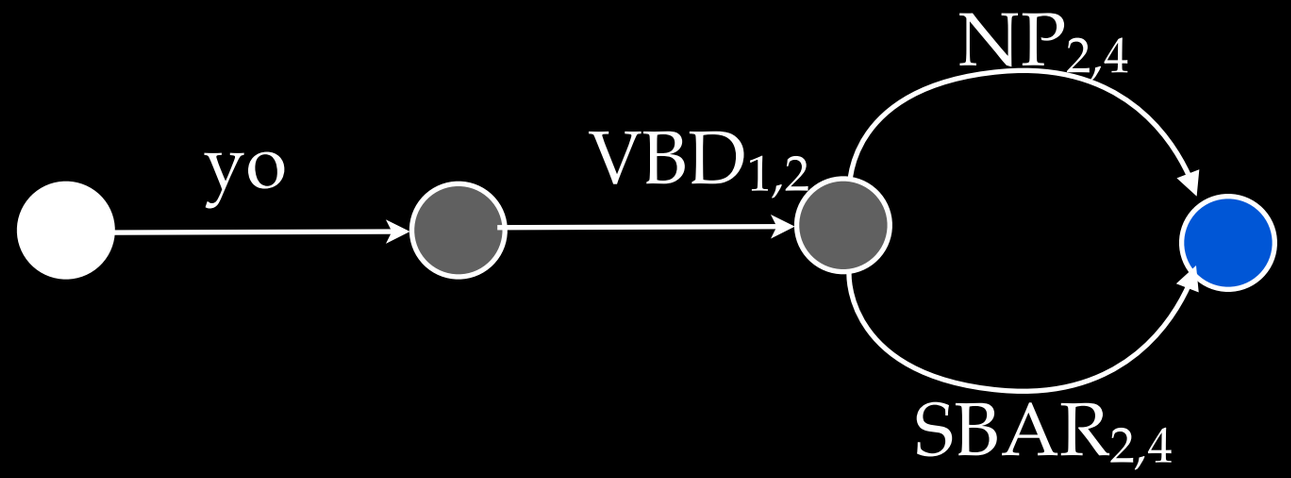
$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



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$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

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$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

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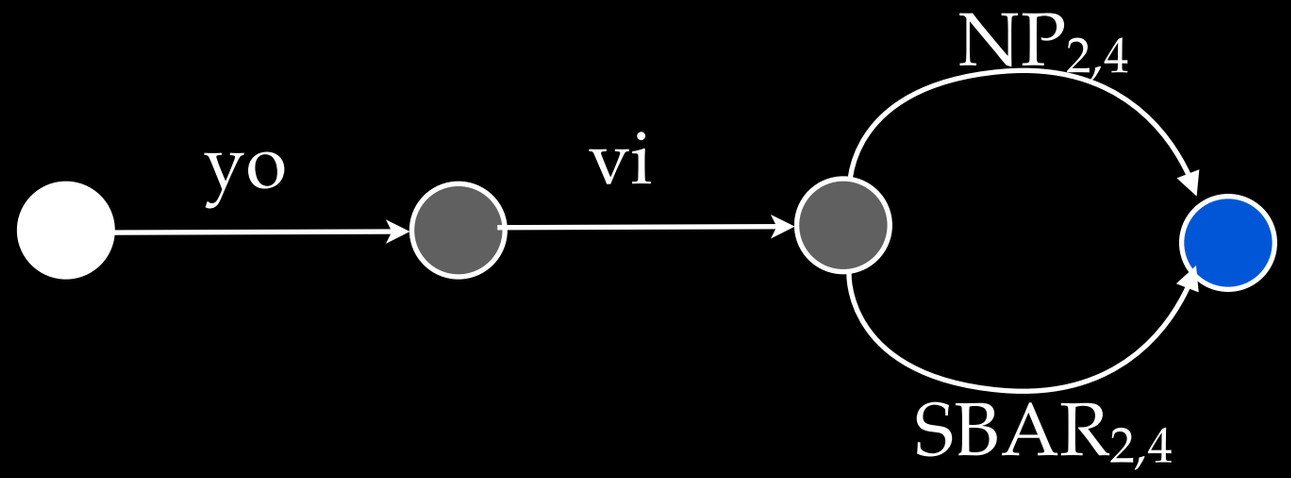
$VBD_{1,2} \rightarrow$ vi



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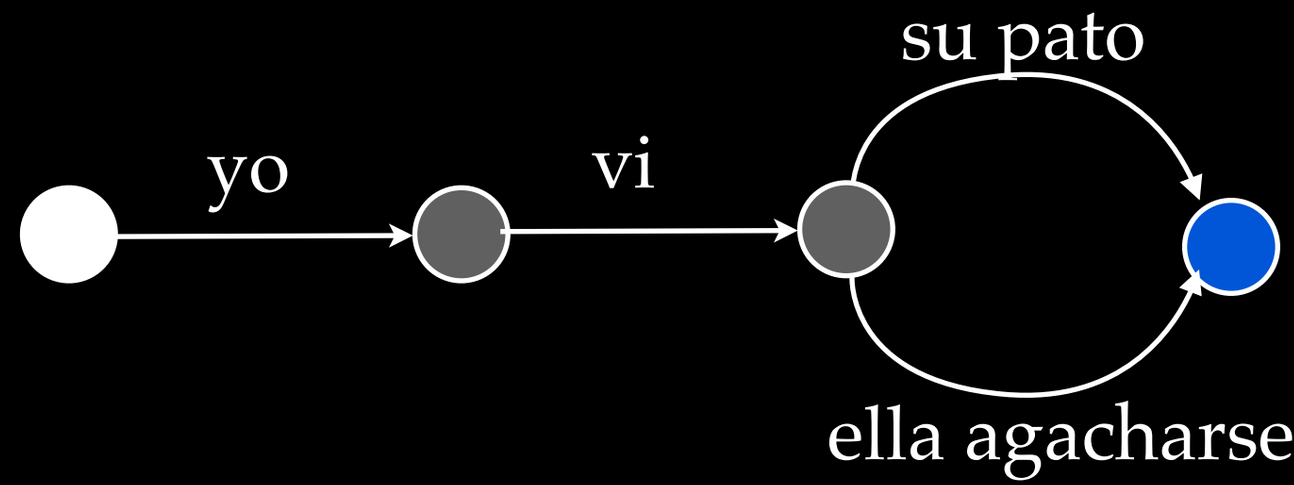
$VBD_{1,2} \rightarrow$ vi



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$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

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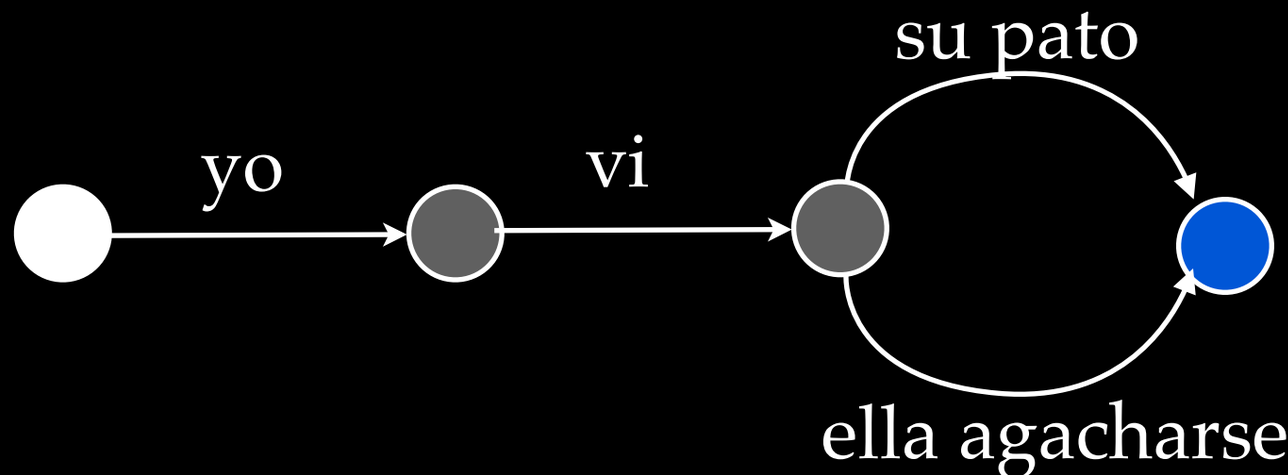

Better: lazy algorithm

Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

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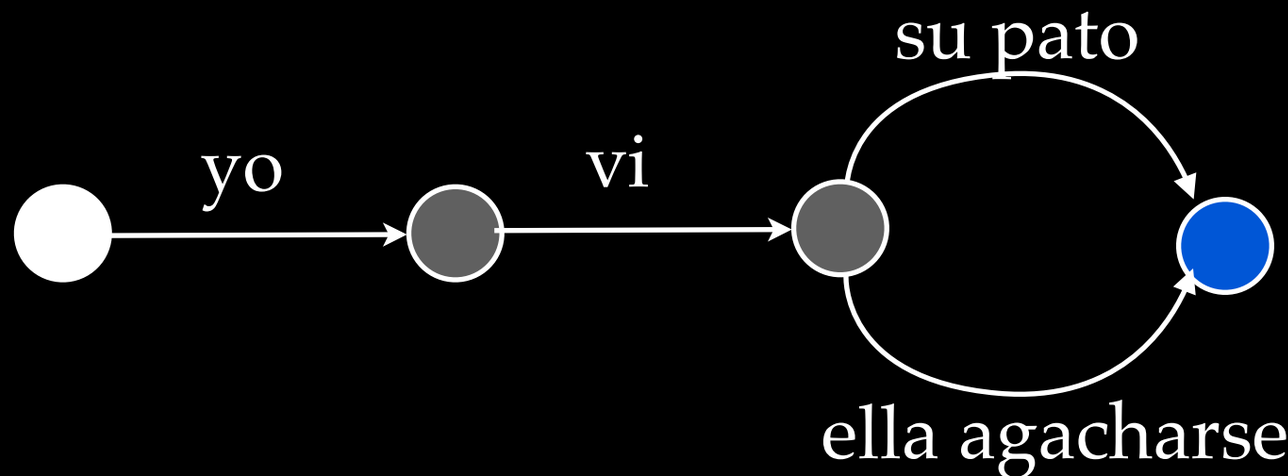
$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi



Better: lazy algorithm

Even better: convert to PDA

Translation as Intersection?

$NN_{3,4} \rightarrow$ pato

$NP_{2,4} \rightarrow PRP\$_{2,3}\ NN_{3,4}$

$PRP_{2,3} \rightarrow$ su

$PRP_{0,1} \rightarrow$ yo

$PRP\$_{2,3} \rightarrow$ ella

$S_{0,4} \rightarrow PRP_{0,1}\ VP_{1,4}$

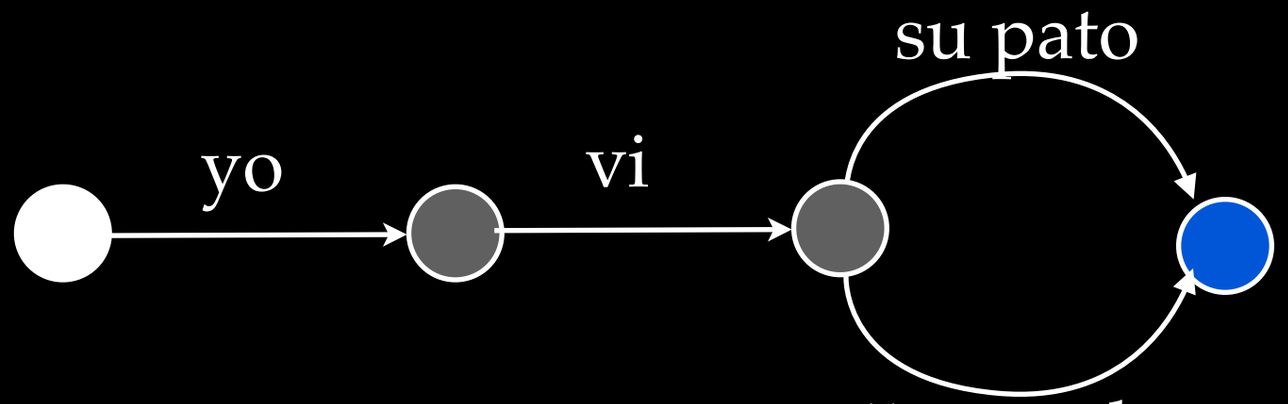
$SBAR_{2,4} \rightarrow PRP_{2,3}\ VB_{3,4}$

$VB_{3,4} \rightarrow$ agacharse

$VP_{1,4} \rightarrow VBD_{1,2}\ NP_{2,4}$

$VP_{1,4} \rightarrow VBD_{1,2}\ SBAR_{2,4}$

$VBD_{1,2} \rightarrow$ vi

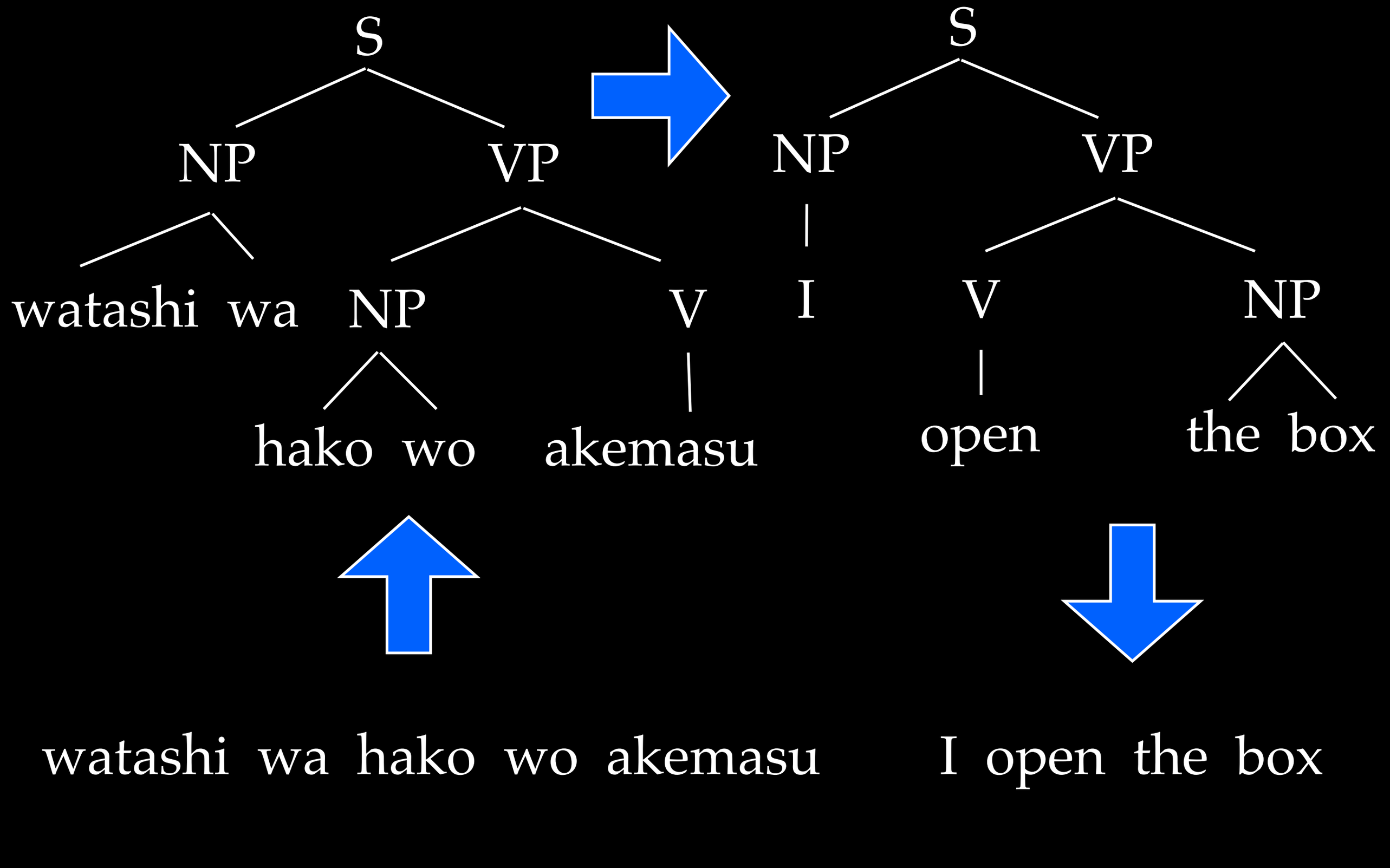


Better: lazy algorithm

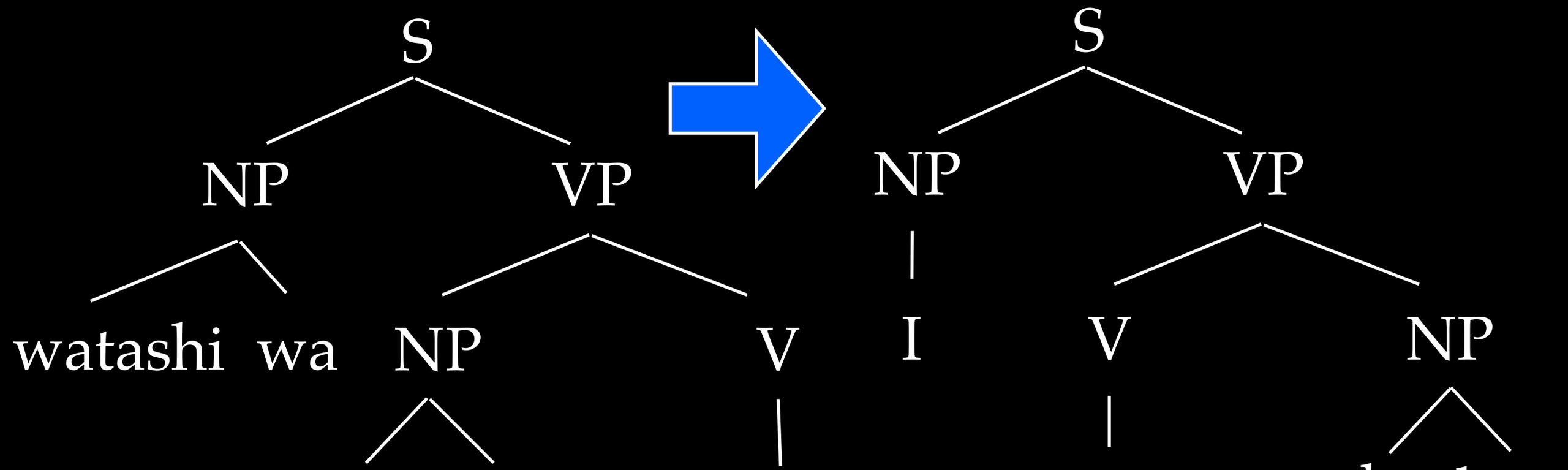
Even better: convert to PDA

Cambridge: best NIST 2009 Arabic system

Parting Thoughts



Parting Thoughts

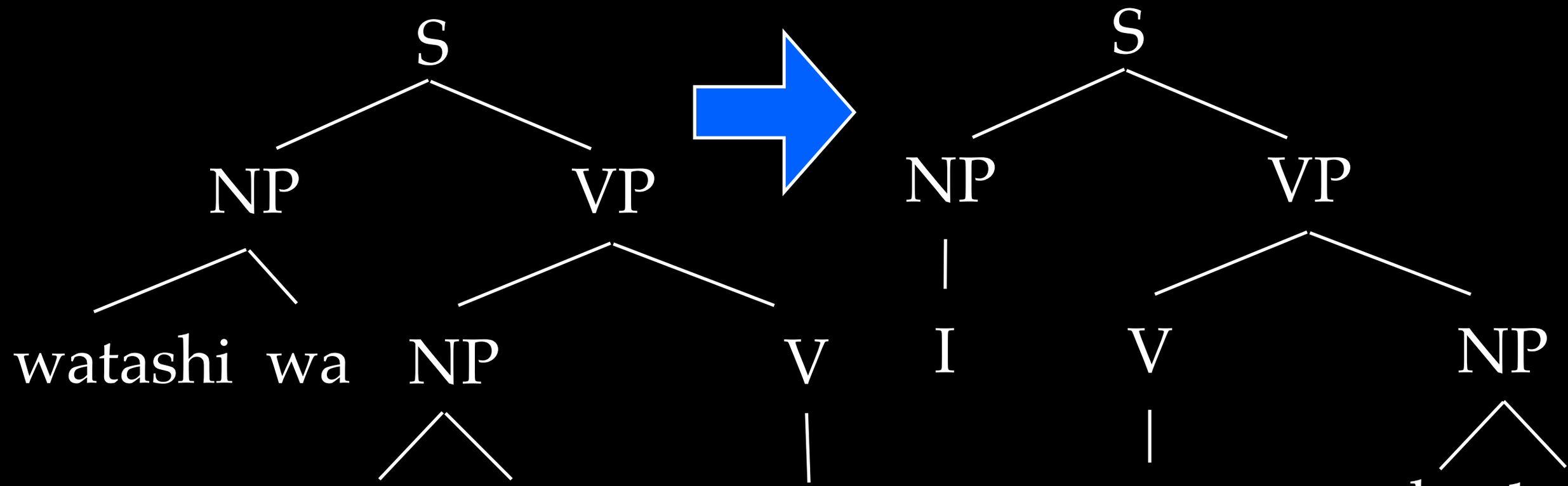


Intersection of weighted CFL and RL

watashi wa hako wo akemasu

I open the box

Parting Thoughts



Intersection of weighted CFL and RL

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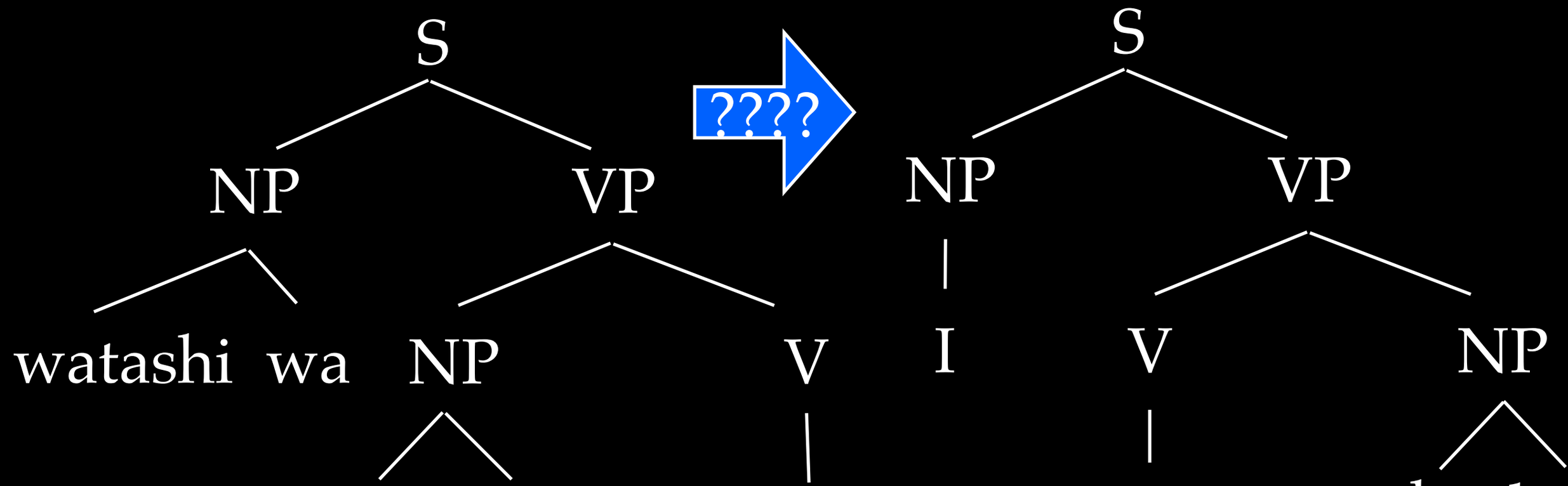
Parting Thoughts



Intersection of weighted CFL and RL

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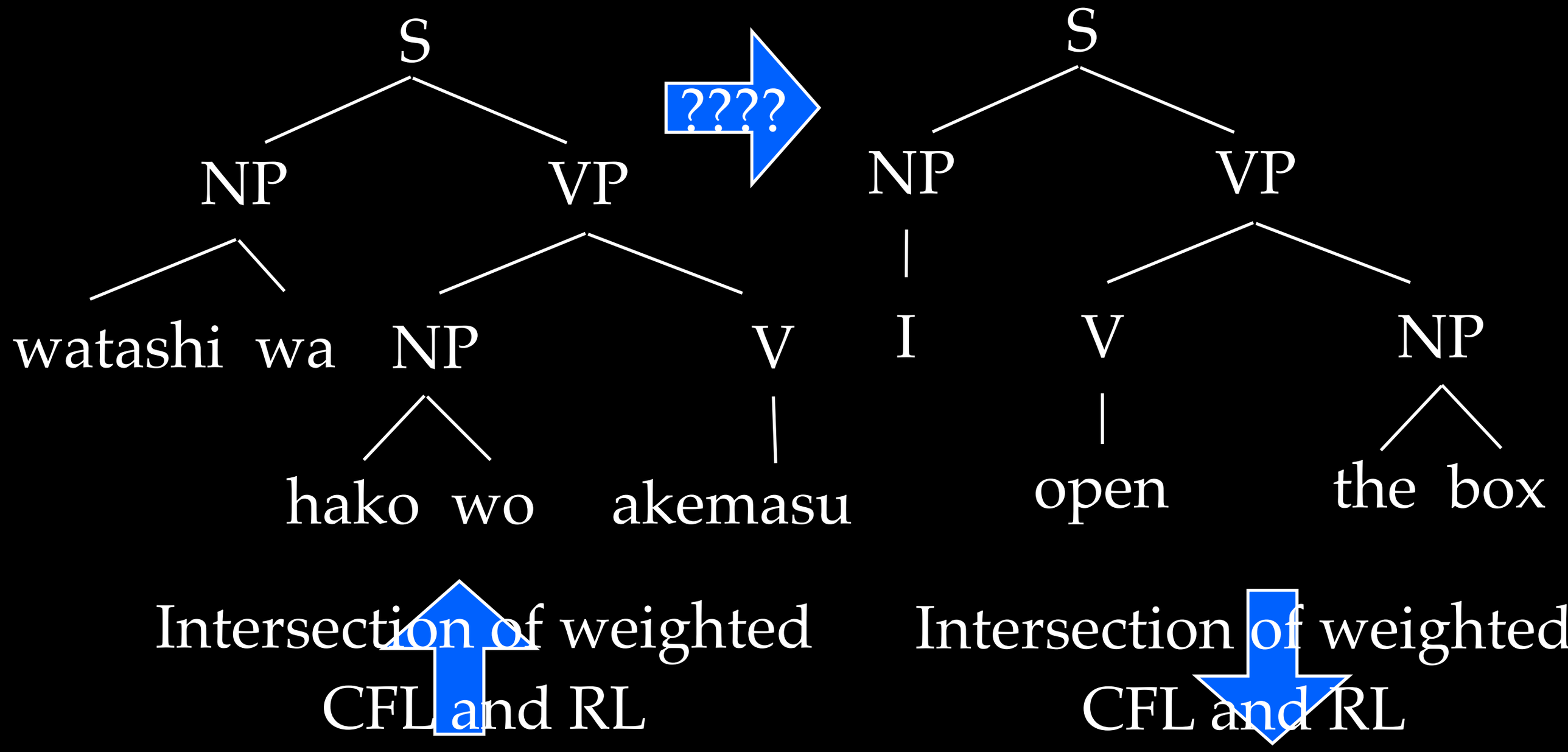

watashi wa hako wo akemasu I open the box

Weighted *tree* languages, automata, and transducers.

Parting Thoughts

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Not all languages are context-free!

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$$\mathcal{L} = \{abc, aabbcc, aaabbbccc, ...\} = \forall_n \in [1, \text{inf}) a^n b^n c^n$$

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CS Theory: *context-sensitive* languages (Turing equivalent)

Parting Thoughts

Not all languages are context-free!

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CS Theory: *context-sensitive* languages (Turing equivalent)

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Tree-adjoining grammar, Combinatory categorial
grammar, many others.