What is Computer Science?
What is Computer Science?

Systems
What is Computer Science?

Systems

Artificial Intelligence
What is Computer Science?

Systems

Artificial Intelligence

Graphics
What is Computer Science?

Systems

Artificial Intelligence

Graphics

Security
What is Computer Science?

Systems

Artificial Intelligence

Graphics

Security

Networking
What is Computer Science?

Systems

Artificial Intelligence

Graphics

Security

Networking

Programming Languages
What is Computer Science?

Systems

Artificial Intelligence

Graphics

Security

Networking

Programming Languages

...
What is Computer Science?

- Systems
- Artificial Intelligence
- Graphics
- Security
- Networking
- Programming Languages

...
What is Computer Science?

Systems

Artificial Intelligence

Graphics

Security

Networking

Programming Languages

Computer Vision

...
What is Computer Science?

- Systems
- Artificial Intelligence
- Graphics
- Security
- Networking
- Programming Languages
- Computer Vision
- Planning
What is Computer Science?

- Systems
- Artificial Intelligence
- Graphics
- Security
- Networking
- Programming Languages

- Computer Vision
- Planning
- Robotics

...
What is Computer Science?

- Systems
- Artificial Intelligence
- Graphics
- Security
- Networking
- Programming Languages
- Computer Vision
- Planning
- Robotics
- Natural Language Processing

...
What is Computer Science?

Systems  
Artificial Intelligence  
Graphics  
Security  
Networking  
Programming Languages

Computer Vision  
Planning  
Robotics  
Natural Language Processing  
...

...
What is Computer Science?

- Systems
- Artificial Intelligence
- Graphics
- Security
- Networking
- Programming Languages
- Computer Vision
- Planning
- Robotics
- Natural Language Processing
- ...
Target language corpus gives examples of well-formed sentences

I will get to it later  See you later  He will do it
Machine Translation

Target language corpus gives examples of well-formed sentences

- I will get to it later
- See you later
- He will do it

Parallel corpus gives translation examples

- I will do it gladly
- You will see later
- Yo lo haré de muy buen grado
- Después lo veras
**Machine Translation**

*Target language corpus gives examples of well-formed sentences*

- I will get to it later
- See you later
- He will do it

*Parallel corpus gives translation examples*

- I will do it gladly
- Yo lo haré de muy buen grado
- You will see later
- Después lo veras

*Machine translation system:*
Machine Translation

Target language corpus gives examples of well-formed sentences

- I will get to it later
- See you later
- He will do it

Parallel corpus gives translation examples

- I will do it gladly
- You will see later
- Yo lo haré de muy buen grado
- Después lo veras

Machine translation system:

Model of translation
Machine Translation

Target language corpus gives examples of well-formed sentences

I will get to it later  See you later  He will do it

Parallel corpus gives translation examples

I will do it gladly  You will see later
Yo lo haré de muy buen grado  Después lo verás

Machine translation system:

Source language

Yo lo haré después

Model of translation

Target language

I will do it later
The Syntactic Structure of Natural Language

Parallel corpus gives translation examples

Yo lo haré de muy buen grado
I will do it gladly

Después lo veras
You will see later

Yo lo haré después
I will do it later

Machine translation system:
The Syntactic Structure of Natural Language

Parallel corpus gives translation examples

\[ \begin{align*}
S & \\
NP & \quad VP \\
\quad PRP & \quad MD & \quad VP \\
\quad PRP & \quad VB & \quad PRP & \quad ADV
\end{align*} \]

I will do it gladly

Yo lo haré de muy buen grado

\[ \begin{align*}
S & \\
NP & \quad VP \\
\quad PRP & \quad MD & \quad VP \\
\quad PRP & \quad VB & \quad ADV
\end{align*} \]

You will see later

Después lo verás

Machine translation system:

Yo lo haré **durante**

Model of translation

I will do it **later**
Parallel corpus gives translation examples

Yo lo haré de muy buen grado
You will see later

I will do it gladly
Después lo verás

Machine translation system:

S
Yo lo haré

S
I will do it

ADV
después

ADV
later

Model of translation
The Syntactic Structure of Natural Language

**Parallel corpus gives translation examples**

```
S → NP VP
   → PRP MD VP
      → PRP VB PRP ADV
```

- I will do it gladly
- Yo lo haré de muy buen grado

```
S → NP VP
   → PRP MD VP
      → PRP VB ADV
```

- You will see later
- Después lo verás

**Machine translation system:**

```
S → ADV
   → Yo lo haré
      → después
```

- I will do it later
- I will do it later

---

Friday, December 2, 2011
A Translation System in 20 Minutes

Context-free grammars as a model of language generation
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations

Tree transformations
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations

Tree transformations

English
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations

Tree transformations

English       ➔       Yoda-speak
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations

Tree transformations

English $\rightarrow$ Yoda-speak

Help you, I can!
Yes! Mm!
A Translation System in 20 Minutes

Context-free grammars as a model of language generation

Large-scale linguistic annotations

Tree transformations

English  $\rightarrow$  Yoda-speak

Help you, I can!
Yes! Mm!

When 900 years old you reach,
look as good, you will not. Hm.
A Context-Free Grammar Describes Generation

"Grammar"
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
A Context-Free Grammar Describes Generation

"Grammar"

S \rightarrow NP \ VP
NP \rightarrow PRP
VP \rightarrow VB
VP \rightarrow VB PRP
A Context-Free Grammar Describes Generation

"Grammar"

S

S → NP VP
NP → PRP
VP → VB
VP → VB PRP
A Context-Free Grammar Describes Generation

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
```

"Grammar"

```
S  ->  NP  VP
NP  ->  PRP
VP  ->  VB
VP  ->  VB  PRP
```
A Context-Free Grammar Describes Generation

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
```

"Grammar"

```
S  ->  NP  VP
NP  ->  PRP
VP  ->  VB
VP  ->  VB  PRP
```
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"
A Context-Free Grammar Describes Generation

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
PRP -> I
```
A Context-Free Grammar Describes Generation

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
PRP -> you
PRP -> I
PRP -> you
```

"Grammar"

```
S   ->   NP  VP
NP   ->   PRP
VP   ->   VB
VP   ->   VB  PRP
```

"Lexicon"

```
PRP   ->   I
PRP   ->   you
```
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
A Context-Free Grammar Describes Generation

**Grammar**

- S → NP VP
- NP → PRP
- VP → VB
- VP → VB PRP

**Lexicon**

- PRP → I
- PRP → you
- VB → know
- VB → help
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP
PRP → you

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
A Context-Free Grammar Describes Generation

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
PRP -> you
VB -> know
VB -> help
```

**Grammar**

```
S -> NP VP
NP -> PRP↓NP
VP -> VB
VP -> VB PRP↓VP
```

**Lexicon**

```
PRP -> I
PRP -> you
VB -> know
VB -> help
```
A Context-Free Grammar Describes Generation

```
Grammar

S → NP VP
NP → PRP
PRP
I
PRP → you
VP → VB
VB → know
VB → help

Lexicon

PRP↓NP → I
PRP → you
VB → know
VB → help
```

```
Grammar refinement
```

Friday, December 2, 2011
A Context-Free Grammar Describes Generation

"Grammar"

\[
S \rightarrow NP \ VP \\
NP \rightarrow PRP \downarrow NP \\
VP \rightarrow VB \\
VP \rightarrow VB \ PRP \downarrow VP
\]

"Lexicon"

\[
PRP \downarrow NP \rightarrow I \\
PRP \rightarrow you \\
VB \rightarrow know \\
VB \rightarrow help \\
PRP \downarrow VP \rightarrow me
\]
A Context-Free Grammar Describes Generation

"Grammar"

S \rightarrow NP \ VP
NP \rightarrow PRP
VP \rightarrow VB
VP \rightarrow VB \ PRP

"Lexicon"

PRP \rightarrow I
PRP \rightarrow you
VB \rightarrow know
VB \rightarrow help
A Context-Free Grammar Describes Generation

```
Grammar
S  ->  NP  VP
NP  ->  PRP
VP  ->  VB
    ->  VB  PRP
    ->  MD  VP
Lexicon
PRP  ->  I
    ->  you
VB  ->  know
    ->  help
```
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
PRP → I
VP → VB
VP → VB PRP
VP → MD VP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
MD → can
A Context-Free Grammar Describes Generation

"Grammar"

S → NP VP
NP → PRP
PRP → I
VP → VB
VP → VB PRP
VP → MD VP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
MD → can
A Context-Free Grammar Describes Generation

"Grammar"

```
S  ->  NP  VP
NP  ->  PRP
VP  ->  VB
VP  ->  VB  PRP
VP  ->  MD  VP
```

"Lexicon"

```
PRP  ->  I
PRP  ->  you
VB  ->  know
VB  ->  help
MD  ->  can
```
A Context-Free Grammar Describes Generation

"Grammar"

S -> NP VP
NP -> PRP
PRP -> I
VP -> VB
VP -> VB PRP
VP -> MD VP

"Lexicon"

PRP -> I
PRP -> you
VB -> know
VB -> help
MD -> can
A grammar can be learned from data (demo)
Left-Corner Parsing Builds Trees For Sentences

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
"Grammar"

S  ->  NP  VP
NP  ->  PRP
VP  ->  VB
VP  ->  VB  PRP

"Lexicon"

PRP  ->  I
PRP  ->  you
VB  ->  know
VB  ->  help
Left-Corner Parsing Builds Trees For Sentences

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
Left-Corner Parsing Builds Trees For Sentences

"Grammar"

S  →  NP  VP
NP  →  PRP
VP  →  VB
VP  →  VB  PRP

"Lexicon"

PRP  →  I
PRP  →  you
VB  →  know
VB  →  help

i  know  you
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)

"Grammar"

S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"

PRP → I
PRP → you
VB → know
VB → help
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)

"Grammar"

S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP

"Lexicon"

PRP -> I
PRP -> you
VB -> know
VB -> help

i know you
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)

"Grammar"
S \rightarrow NP \, VP
NP \rightarrow PRP
VP \rightarrow VB
VP \rightarrow VB \, PRP

Left corners

"Lexicon"
PRP \rightarrow I
PRP \rightarrow you
VB \rightarrow know
VB \rightarrow help
parse_next(S, 1)
complete(S, (PRP i), 1)
parse_next(S, 1)
complete(S, (PRP i), 1)
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
complete(S, (PRP i), 1)
complete(S, (NP (PRP i)), 1)
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)

"Grammar"

S \rightarrow NP \ VP
NP \rightarrow PRP
VP \rightarrow VB
VP \rightarrow VB PRP

Left corners

"Lexicon"

PRP \rightarrow I
PRP \rightarrow you
VB \rightarrow know
VB \rightarrow help
Left-Corner Parsing Builds Trees For Sentences

```
parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
```

```
S → NP VP
NP → PRP
VP → VB
VP → VB PRP
```

```
S
   NP   VP
      PRP
             i
               know
               you
```
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)

"Grammar"
  S \rightarrow NP VP
  NP \rightarrow PRP
  VP \rightarrow VB
  VP \rightarrow VB PRP

"Lexicon"
  PRP \rightarrow I
  PRP \rightarrow you
  VB \rightarrow know
  VB \rightarrow help
parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
    complete(S, (PRP i), 1)
    complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
    complete(VP, (VB know), 2)
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
  complete(VP, (VP (VB know)), 2)

S

NP
  PRP
    i
  VP
    know
    you

"Grammar"
S → NP VP
NP → PRP
VP → VB
VP → VB PRP

"Lexicon"
PRP → I
PRP → you
VB → know
VB → help
parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
  complete(VP, (VP (VB know)), 2)
Left-Corner Parsing Builds Trees For Sentences

```
parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
  complete(VP, (VP (VB know)), 2)
complete(S, (S ...), 1)
```

"Grammar"

```
S  -->  NP  VP
NP  -->  PRP
VP  -->  VB
    -->  VB  PRP
```

"Lexicon"

```
PRP  -->  I
PRP  -->  you
VB  -->  know
    -->  help
```

```
S

NP        VP
  PRP       VB
    i       know      you
```
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
complete(S, (PRP i), 1)
complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
complete(VP, (VB know), 2)

"Grammar"
S \rightarrow NP VP
NP \rightarrow PRP
VP \rightarrow VB
VP \rightarrow VB PRP

"Lexicon"
PRP \rightarrow I
PRP \rightarrow you
VB \rightarrow know
VB \rightarrow help

S
   NP
      PRP
         i
         know
         you
Left-Corner Parsing Builds Trees For Sentences

```
parse_next(S, 1)
    complete(S, (PRP i), 1)
    complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
    complete(VP, (VB know), 2)
```

"Grammar"

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
```

"Lexicon"

```
PRP -> I
PRP -> you
VB -> know
VB -> help
```
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
  complete(VP, (VP (VB know) (PRP you)), 2)
Left-Corner Parsing Builds Trees For Sentences

parse_next(S, 1)
    complete(S, (PRP i), 1)
    complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
    complete(VP, (VB know), 2)
    complete(VP, (VP (VB know) (PRP you)), 2)
Left-Corner Parsing Builds Trees For Sentences

```
parse_next(S, 1)
  complete(S, (PRP i), 1)
  complete(S, (NP (PRP i)), 1)
parse_next(VP, 2)
  complete(VP, (VB know), 2)
  complete(VP, (VP (VB know) (PRP you)), 2)
complete(S, (S ...), 1)
```

"Grammar"

```
S -> NP VP
NP -> PRP
VP -> VB
VP -> VB PRP
```

"Lexicon"

```
PRP -> I
PRP -> you
VB -> know
VB -> help
```