Parsing Expression Grammars:
A Recognition-Based Syntactic Foundation

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Designing a Language Syntax

Designing a Language Syntax

Textbook Method

1. Formalize syntax via context-free grammar
2. Write a YACC parser specification
3. Hack on grammar until “near-*LALR(1)*”
4. Use generated parser

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Pragmatic Method

1. Specify syntax informally
2. Write a recursive descent parser

What exactly does a CFG describe?

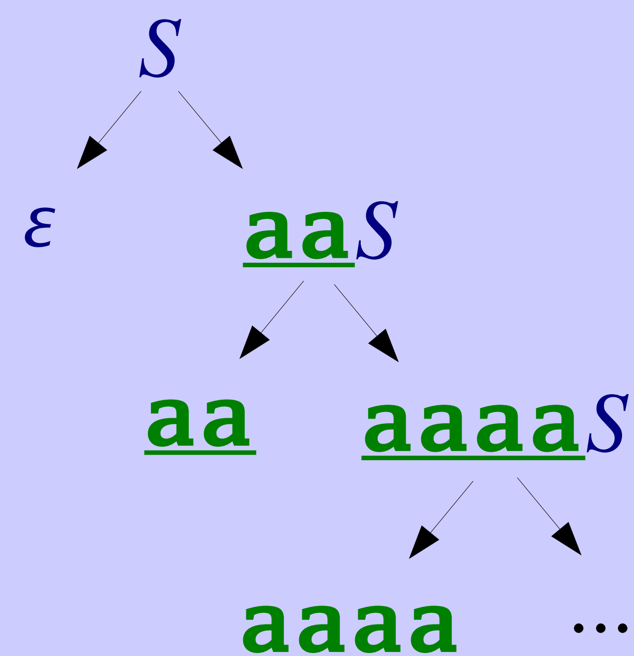
Short answer:

a rule system to **generate** language strings

Example CFG:

$S \rightarrow$ **aa**S

$S \rightarrow \varepsilon$



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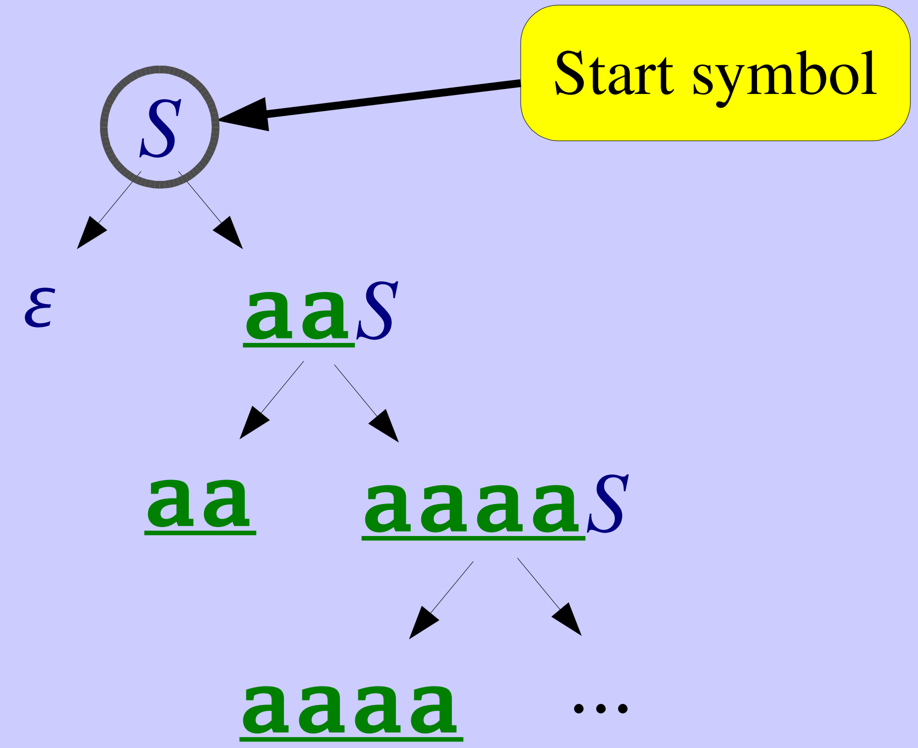

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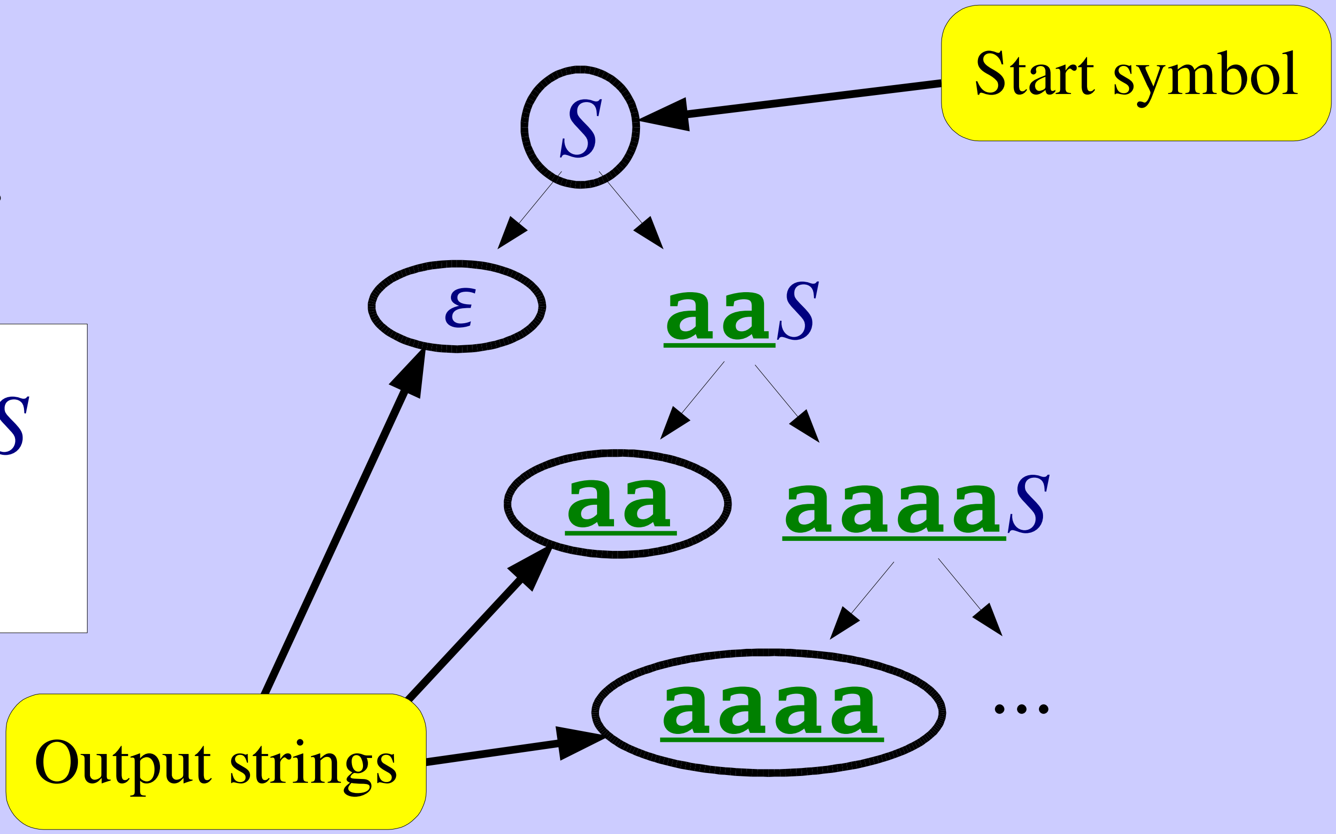


What exatly do we *want* to describe?

Proposed answer:

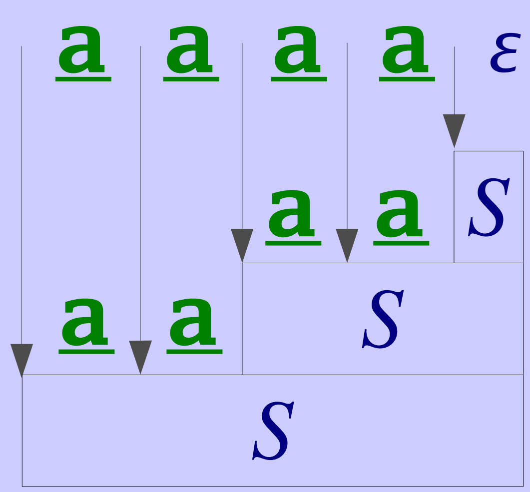
a rule system to **recognize** language strings

Parsing Expression Grammar (PEG)

models **recursive descent parsing practice**

Example PEG:

$$S \leftarrow \underline{\mathbf{aa}}S \;/\; \varepsilon$$



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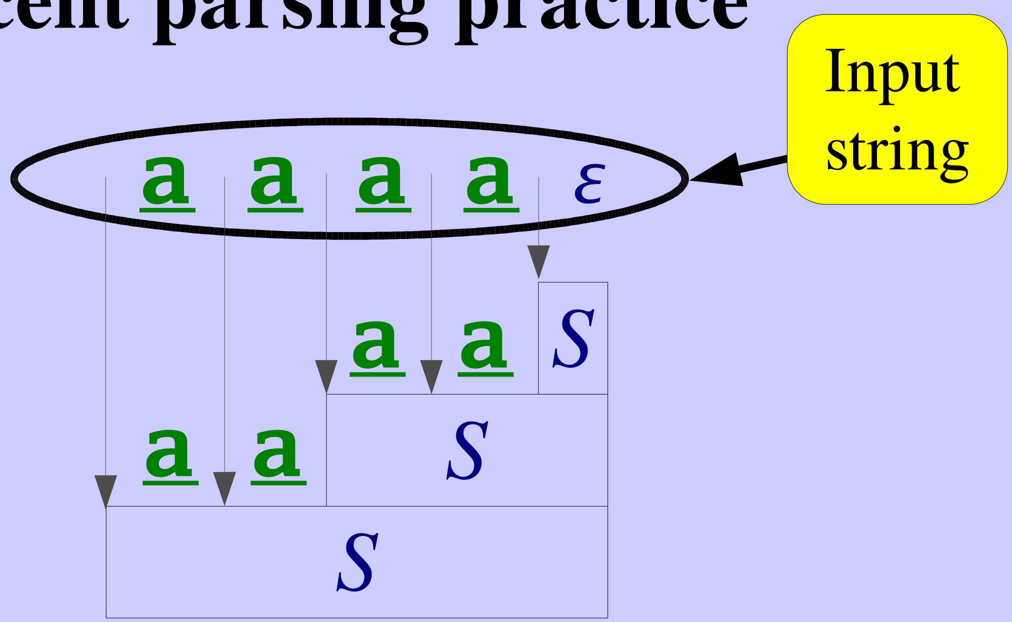

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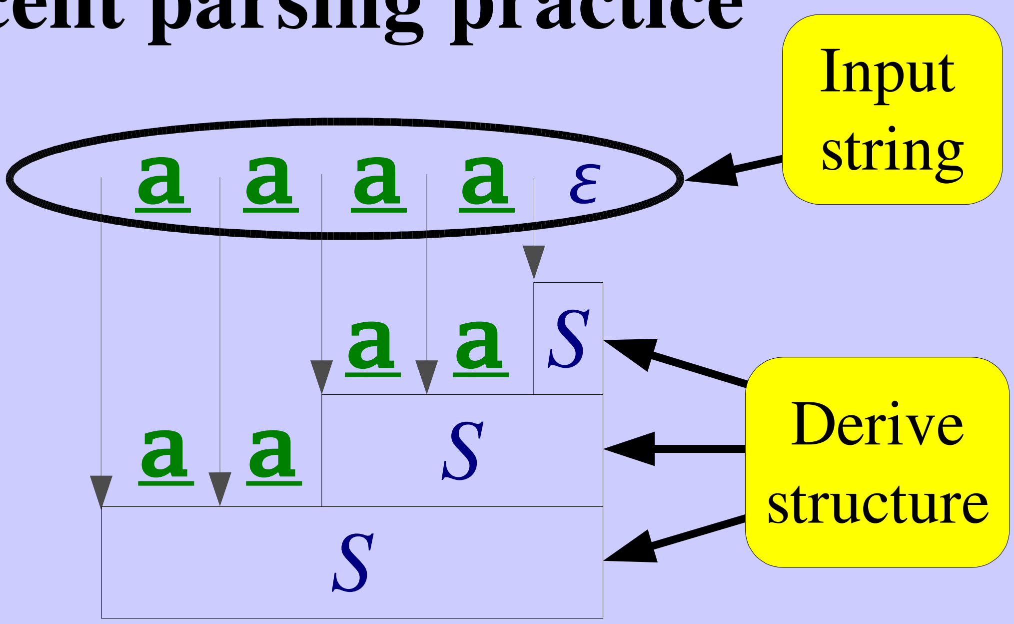

Take-Home Points

Key benefits of PEGs:

- **Simplicity, formalism, analyzability** of CFGs
- **Closer match** to syntax practices
  - More expressive than deterministic CFGs (*LL*/*LR*)
  - More of the "right kind" of expressiveness: *prioritized choice, greedy rules, syntactic predicates*
  - Unlimited lookahead, backtracking
- **Linear-time parsing** for ***any*** PEG

What kind of recursive descent parsing?

Key assumptions:

- Parsing functions are **stateless**:
  depend only on input string
- Parsing functions **make decisions locally**:
  return at most one result (success/failure)

Parsing Expression Grammars

Consists of: (Σ, N, R, e_S)

- Σ: finite set of *terminals* (character set)
- N: finite set of *nonterminals*
- R: finite set of rules of the form "$A \leftarrow e$", where $A \in N$, e is a *parsing expression*.
- e_S: a parsing expression called the *start expression*.

Parsing Expressions

ε	the empty string
<u>**a**</u>	terminal (<u>**a**</u> $\in \Sigma$)
A	nonterminal ($A \in N$)
$e_1\ e_2$	a sequence of parsing expressions
$e_1\ /\ e_2$	*prioritized choice* between alternatives
$e^?$, e^*, e^+	optional, zero-or-more, one-or-more
$\&e$, $!e$	syntactic predicates

How PEGs Express Languages

Given input string s, a parsing expression either:

- **Matches** and consumes a prefix s' of s.
- **Fails** on s.

Example:

$S \leftarrow$ **bad**

S matches "**badder**"
S matches "**baddest**"
S *fails* on "**abad**"
S *fails* on "**babe**"

Prioritized Choice with Backtracking

S* ← *A* / *B means:

> **"To parse an *S*, *first* try to parse an *A*.**
> **If *A* fails, *then* backtrack and try to parse a *B*."**

Example:

$S \leftarrow$ `if` C `then` S `else` S / `if` C `then` S

S matches "`if C then S foo`"

S matches "`if C then S1 else S2`"

S *fails* on "`if C else S`"

Prioritized Choice with Backtracking

S ← ***A* / *B*** means:

> **"To parse an *S*, *first* try to parse an *A*.
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Example from the C++ standard:

> *"An **expression-statement** ... can be indistinguishable from a **declaration** ... In those cases the **statement** is a **declaration**."*

statement ← *declaration* /
expression-statement

Greedy Option and Repetition

$A \leftarrow e^?$ equivalent to $A \leftarrow e \,/\, \varepsilon$

$A \leftarrow e^*$ equivalent to $A \leftarrow e\ A \,/\, \varepsilon$

$A \leftarrow e^+$ equivalent to $A \leftarrow e\ e^*$

Example:

$I \leftarrow L^+$

$L \leftarrow$ `a` / `b` / `c` / …

I matches "`foobar`"

I matches "`foo(bar)`"

I *fails* on "`123`"

Syntactic Predicates

And-predicate: ***&e*** succeeds whenever *e* does, *but consumes no input* [Parr '94, '95]

Not-predicate: **!*e*** succeeds whenever *e* fails

Example:

$A \leftarrow$ `foo` &(`bar`)
$B \leftarrow$ `foo` !(`bar`)

A matches "`foobar`"
A *fails* on "`foobie`"
B matches "`foobie`"
B *fails* on "`foobar`"

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Example:

$C \leftarrow B\ I^*\ E$

$I \leftarrow\ !E\ (C\ /\ T)$

$B \leftarrow$ `(*`

$E \leftarrow$ `*)`

$T \leftarrow$ *[any terminal]*

C matches "**(*ab*)cd**"

C matches "**(*a(*b*)c*)**"

C fails on "**(*a(*b*)**"

Syntactic Predicates

And-predicate: **&*e*** succeeds whenever *e* does,
but consumes no input [Parr '94, '95]

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Example:

Begin marker

C ← *B I* E*
I ← !*E* (*C* / *T*)
B ← **(***
E ← ***)**
T ← *[any terminal]*

C matches "**(*ab*)cd**"
C matches "**(*a(*b*)c*)**"
C fails on "**(*a(*b*)**"

Syntactic Predicates

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Example:

Internal elements

$C \leftarrow B\ I{*}\ E$

$I \leftarrow\ !E\ (C\ /\ T)$

$B \leftarrow$ `(*`

$E \leftarrow$ `*)`

$T \leftarrow$ *[any terminal]*

C matches "`(*ab*)cd`"

C matches "`(*a(*b*)c*)`"

C *fails* on "`(*a(*b*)`"

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$B \leftarrow$ `(*`

$E \leftarrow$ `*)`

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End marker

C matches "**(*ab*)cd**"

C matches "**(*a(*b*)c*)**"

C *fails* on "**(*a(*b*)**"

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Example:

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➔ $I \leftarrow\ !E\ (C\ /\ T)$
$B \leftarrow$ `(*`
$E \leftarrow$ `*)`
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Example:

Only if an end marker *doesn't* start here...

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$B \leftarrow$ **(***

$E \leftarrow$ ***)**

$T \leftarrow$ *[any terminal]*

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Syntactic Predicates

And-predicate: **&*e*** succeeds whenever *e* does,
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Example:

C ← *B I* E*
I ← *!E (C / T)*
B ← **(***
E ← ***)**
T ← *[any terminal]*

Only if an end marker *doesn't* start here...

...consume a nested comment,
or else consume any single character.

C matches "**(*a(*b*)c*)**"
C *fails* on "**(*a(*b*)**"

Syntactic Predicates

And-predicate: ***&e*** succeeds whenever *e* does, *but consumes no input* [Parr '94, '95]

Not-predicate: ***!e*** succeeds whenever *e* fails

Example:

$C \leftarrow B\ I^*\ E$

$I \leftarrow\ !E\ (C\ /\ T)$

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$E \leftarrow$ ***)**

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C matches "**(*ab*)cd**"

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C *fails* on "**(*a(*b*)**"

Unified Grammars

PEGs can express both ***lexical*** *and* ***hierarchical*** syntax of realistic languages in one grammar

- *Example (in paper):*
  Complete self-describing PEG in 2/3 column
- *Example (on web):*
  Unified PEG for Java language

Lexical/Hierarchical Interplay

Unified grammars create new design opportunities

Example:

E ← *S* / (*E*) / ...
S ← “ *C** “
C ← \(*E*) /
!“ !\ *T*
T ← *[any terminal]*

To get Unicode “∀”,
instead of “\u2200”,
write “\(0x2200)”
or “\(8704)”
or “\(FOR_ALL)”

Lexical/Hierarchical Interplay

Unified grammars create new design opportunities

Example:

General-purpose expression syntax

E ← *S* / (*E*) / ...
S ← “ *C** “
C ← \(*E*) /
!“ !\ *T*
T ← *[any terminal]*

To get Unicode “∀”,
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Lexical/Hierarchical Interplay

Unified grammars create new design opportunities

Example:

String literals

$$
\begin{aligned}
E &\leftarrow S \;/\; \underline{(}\; E \;\underline{)} \;\; \ldots \\
S &\leftarrow \underline{``}\; C^* \;\underline{``} \\
C &\leftarrow \underline{\backslash(}\; E \;\underline{)} \;/ \\
  &\quad\;\; !\underline{``}\;\; !\underline{\backslash}\;\; T \\
T &\leftarrow [\mathit{any\ terminal}]
\end{aligned}
$$

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Lexical/Hierarchical Interplay

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Example:

Quotable characters

E ← *S* / (*E*) / …
S ← “ *C** “
C ← \(*E*) /
  !“ !\ *T*
T ← *[any terminal]*

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Example:

E ← *S* / (*E*) / ...
S ← " *C** "
C ← \(*E*) /
!" !\ *T*
T ← *[any terminal]*

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Formal Properties of PEGs

- Express all deterministic languages - *LR(k)*
- Closed under union, intersection, complement
- Some non-context free languages, e.g., $\mathbf{\underline{a}}^n\mathbf{\underline{b}}^n\mathbf{\underline{c}}^n$
- Undecidable whether $L(G) = \emptyset$
- Predicate operators can be eliminated
  - ...but the process is non-trivial!

Minimalist Forms

Predicate-free PEG	Any PEG
⇩	⇩
TS [Birman '70/'73]	gTS [Birman '70/'73]
TDPL [Aho '72]	GTDPL [Aho '72]

$A \leftarrow \varepsilon$

$A \leftarrow$ <u>**a**</u>

$A \leftarrow f$

$A \leftarrow BC \,/\, D$

⇔

$A \leftarrow \varepsilon$

$A \leftarrow$ <u>**a**</u>

$A \leftarrow f$

$A \leftarrow B[C, D]$

Formal Contributions

- Generalize TDPL/GTDPL with more expressive *structured parsing expression* syntax
- *Negative* syntactic predicate - !*e*
- *Predicate elimination* transformation
  - Intermediate stages depend on generalized parsing expressions
- *Proof of equivalence* of TDPL and GTDPL

What *can't* PEGs express directly?

- Ambiguous languages

  That's what CFGs were designed for!

- Globally disambiguated languages?
  - $\{\mathbf{a},\mathbf{b}\}^n\ \mathbf{a}\ \{\mathbf{a},\mathbf{b}\}^n$?
- State- or semantic-dependent syntax
  - C, C++ `typedef` symbol tables
  - Python, Haskell, ML layout

Generating Parsers from PEGs

Recursive-descent parsing

- ☞ Simple & direct, but exponential-time if not careful

Packrat parsing [Birman '70/'73, Ford '02]

- ☞ Linear-time, but can consume substantial storage

Classic LL/LR algorithms?

- ☞ Grammar restrictions, but both time- & space-efficient

Conclusion

PEGs model common parsing practices

- *Prioritized choice, greedy rules, syntactic predicates*

PEGs naturally complement CFGs

- CFG: *generative* system, for *ambiguous* languages
- PEG: *recognition-based*, for *unambiguous* languages

For more info:

http://pdos.lcs.mit.edu/~baford/packrat

(or Google for "**Packrat Parsing**")