10. PEGs, Packrats and Parser Combinators

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Thanks to Bryan Ford for his kind permission to reuse and adapt the slides of his POPL 2004 presentation on PEGs.
http://www.brynosaurus.com/

UNIVERSITÄT BERN

Roadmap

- Domain Specific Languages
- Parsing Expression Grammars
- Packrat Parsers
- Parser Combinators

Sources

> **Parsing Techniques — A Practical Guide**
  — Grune & Jacobs, Springer, 2008
  — *[Chapter 15.7 — Recognition Systems]*

> **"Parsing expression grammars: a recognition-based syntactic foundation"**
  — Ford, POPL 2004, doi:10.1145/964001.964011

> **"Packrat parsing: simple, powerful, lazy, linear time"**
  — Ford, ICFP 02, doi:10.1145/583852.581483

> **The Packrat Parsing and Parsing Expression Grammars Page:**
  — http://pdos.csail.mit.edu/~baford/packrat/

> **Dynamic Language Embedding With Homogeneous Tool Support**
  — Renggli, PhD thesis, 2010, http://scg.unibe.ch/bib/Reng10d

Roadmap

> **Domain Specific Languages**
> Parsing Expression Grammars
> Packrat Parsers
> Parser Combinators

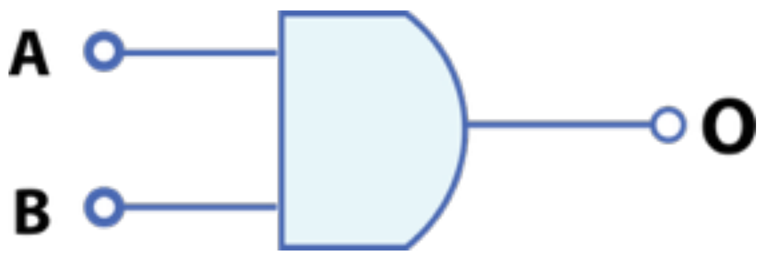
Domain Specific Languages

> A DSL is a specialized language targeted to a particular problem domain
  - Not a GPL
  - May be *internal* or *external* to a host GPL
  - Examples: SQL, HTML, Makefiles

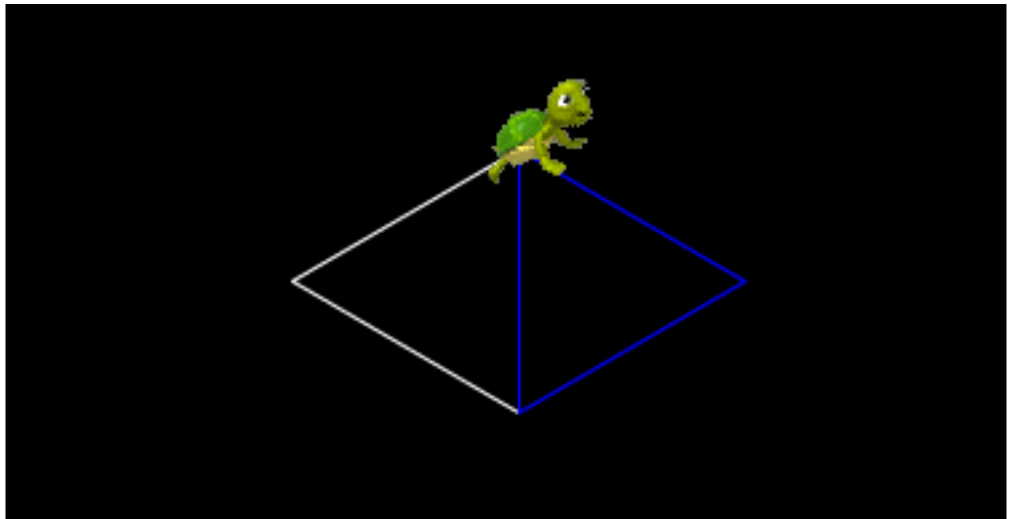
External DSL's (Examples)

```vhdl
-- this is the entity
entity ANDGATE is
  port (
    A : in std_logic;
    B : in std_logic;
    O : out std_logic);
end entity ANDGATE;

-- this is the architecture
architecture RTL of ANDGATE is
begin
  O <= A and B;
end architecture RTL;
```




```
pencolor white
fd 100
rt 120
fd 100
rt 120
fd 100
rt 60
pencolor blue
fd 100
rt 120
fd 100
rt 120
fd 100
rt 60
```



Internal DSLs

A "Fluent Interface" is a DSL that hijacks the host syntax

Function sequencing

```
computer();
   processor();
      cores(2);
      i386();
   disk();
      size(150);
   disk();
      size(75);
      speed(7200);
      sata();
   end();
```

Function nesting

```
computer(
   processor(
      cores(2),
      Processor.Type.i386),
   disk(
      size(150)),
   disk(
      size(75),
      speed(7200),
      Disk.Interface.SATA));
```

Function chaining

```
computer()
   .processor()
      .cores(2)
      .i386()
      .end()
   .disk()
      .size(150)
      .end()
   .disk()
      .size(75)
      .speed(7200)
      .sata()
      .end()
   .end();
```

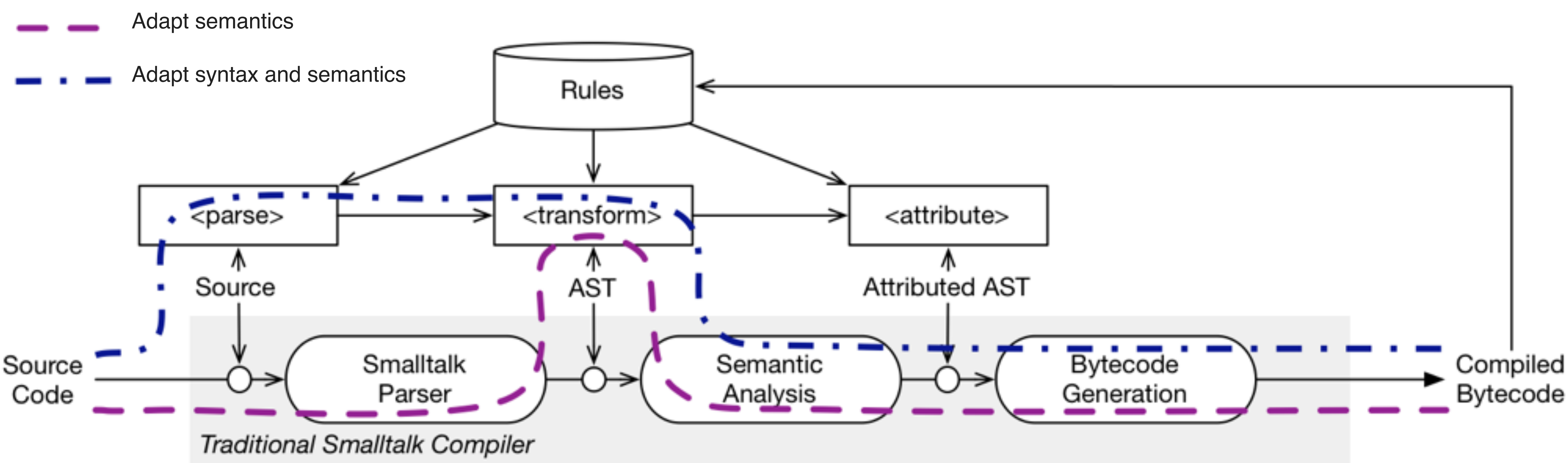
Fluent Interfaces

- *Other approaches:*
  - —Higher-order functions
  - —Operator overloading
  - —Macros
  - —Meta-annotations
  - —…

```
sizer.FromImage(i)
 .ReduceByPercent(x)
 .Pixalize()
 .ReduceByPercent(x)
 .OutputImageFormat(ImageFormat.Jpeg)
 .ToLocation(o)
 .Save();
```

Embedded languages

An *embedded language* may adapt the syntax or semantics of the host language



We will explore some techniques used to specify external and embedded DSLs

Roadmap

> Domain Specific Languages
> **Parsing Expression Grammars**
> Packrat Parsers
> Parser Combinators

Recognition systems

"Why do we cling to a **generative** mechanism for the description of our languages, from which we then laboriously derive recognizers, when almost all we ever do is **recognizing** text? **Why don't we specify our languages directly by a recognizer**?"

Some people answer these two questions by "We shouldn't" and "We should", respectively.

— Grune & Jacobs, 2008

Designing a Language Syntax

Textbook Method

1. Formalize syntax via context-free grammar
2. Write a parser generator (.*CC) specification
3. Hack on grammar until "nearLALR(1)"
4. Use generated parser

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

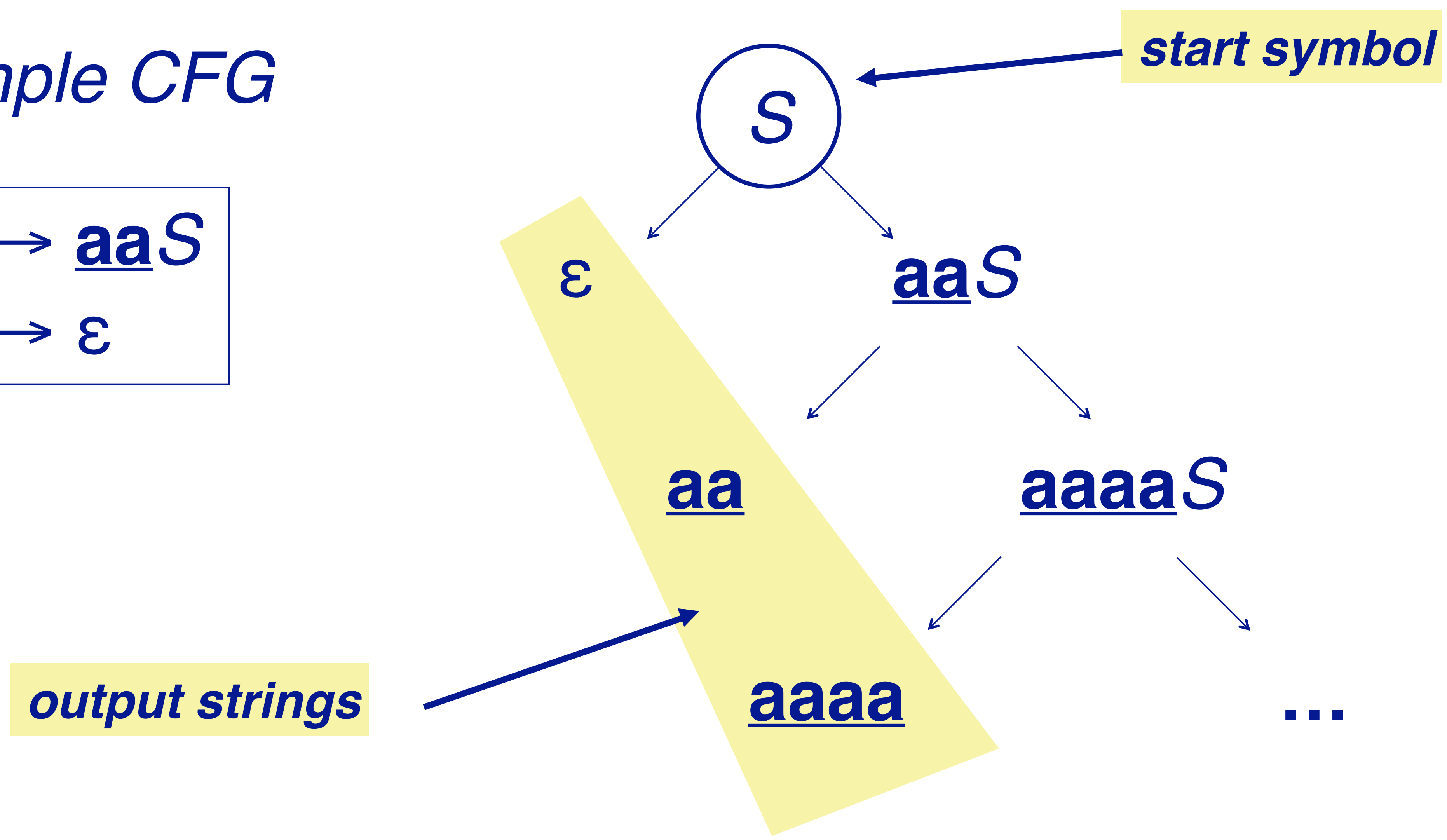
What exactly does a CFG describe?

Short answer: a rule system to *generate* language strings

Example CFG

$S \rightarrow \underline{\textbf{aa}}S$

$S \rightarrow \varepsilon$



http://www.brynosaurus.com/pub/lang/peg-slides.pdf

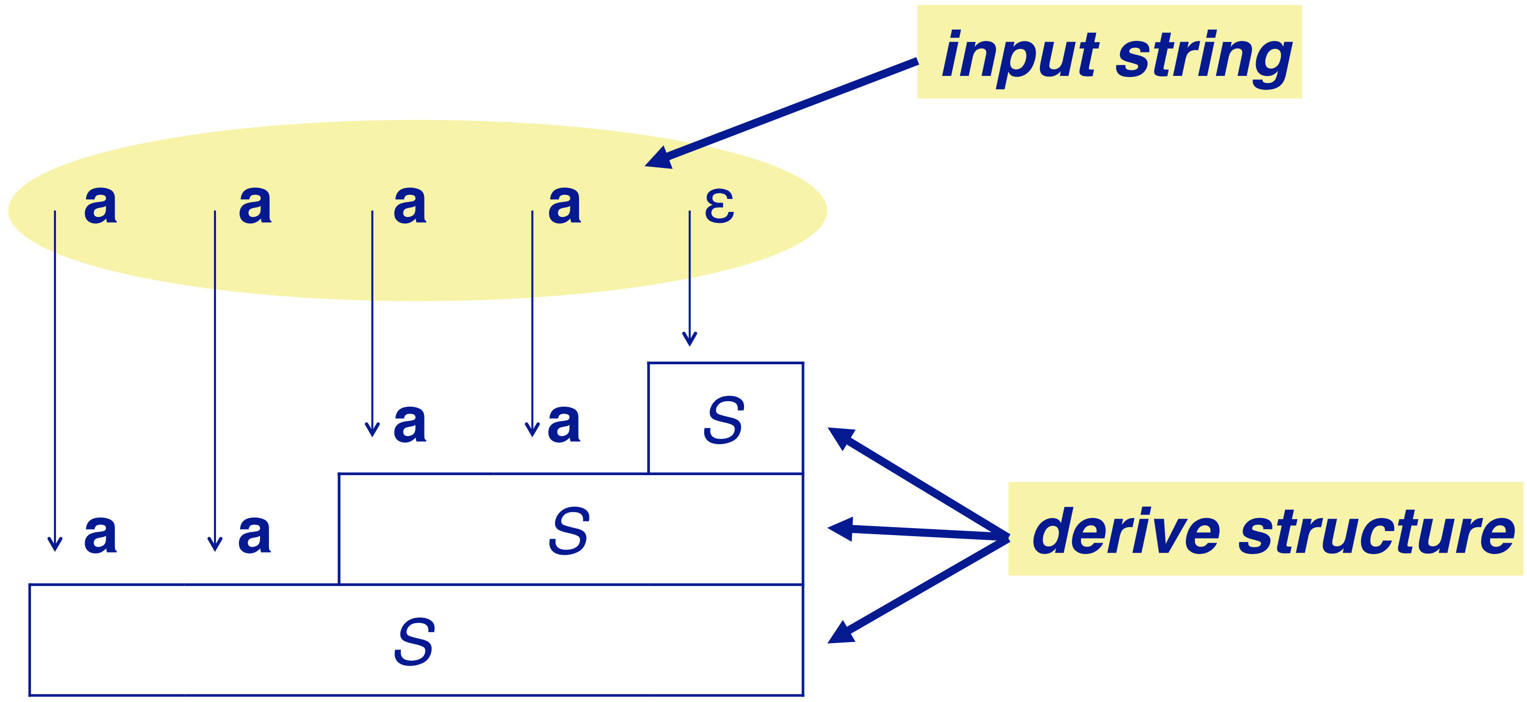
What exactly do we *want* to describe?

Proposed answer: a rule system to *recognize* language strings

Parsing Expression Grammars (PEGs) model recursive descent parsing best practice

Example PEG

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



http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Key benefits of PEGs

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

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Key assumptions

Parsing functions must

1. be stateless - depend only on input *string*
2. make decisions locally - return one result or fail

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Parsing Expression Grammars

- A ***PEG*** P = (Σ, N, R, e_S)
  - Σ : a finite set of *terminals* (character set)
  - N : finite set of *non-terminals*
  - R : finite set of rules of the form "$A \leftarrow e$", where $A \in N$, and e is a *parsing expression*
  - e_S : the *start expression* (a parsing expression)

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Parsing Expressions

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

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

How PEGs express languages

- Given an input string **s**, a parsing expression **e** either:
  - —Matches and consumes a prefix **s'** of **s**, or
  - —Fails on **s**

S ← **bad**

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

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Prioritized choice with backtracking

$S \leftarrow A \mathbin{/} B$

means: first try to parse an A.
If A fails, then backtrack and try to parse a B.

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

S matches "**if** C **then** S foo"
S matches "**if** C **then** S_1 **else** S_2"
S *fails* on "**if** C **else** S"

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Greedy option and repetition

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

$I \leftarrow L^+$
$L \leftarrow$ **a** / **b** / **c** / …

I matches "**foobar**"
I *fails* on "**123**"

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Syntactic Predicates

&e succeeds whenever e does, *but consumes no input*

!e succeeds whenever e fails, *but consumes no input*

A ←	**foo**	&(**bar**)
B ←	**foo**	!(**bar**)

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

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

Example: nested comments

Comment	←	Begin Internal* End
Internal	←	!End (Comment / Terminal)
Begin	←	**/****
End	←	***/**
Terminal	←	[*any character*]

C matches "**/**ab*/cd**"

C matches "**/**a/**b*/c*/**"

C *fails* on "**/**a/**b*/**

Formal properties of PEGs

- **Expresses all deterministic languages — LR(k)**
- **Closed under union, intersection, complement**
- **Expresses some non-context free languages**
  —e.g., $\mathbf{a}^n\mathbf{b}^n\mathbf{c}^n$
- Undecidable whether $L(G) = \varnothing$

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

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Top-down parsing techniques

Predictive parsers

- use lookahead to decide which rule to trigger
- fast, linear time

Backtracking parsers

- try alternatives in order; backtrack on failure
- simpler, more expressive

(possibly exponential time!)

Example

Add	←	Mul <u>+</u> Add / Mul
Mul	←	Prim <u>*</u> Mul / Prim
Prim	←	<u>(</u> Add <u>)</u> / Dec
Dec	←	<u>0</u> / <u>1</u> / … / <u>9</u>

***NB:** This is a <u>scannerless parser</u> — the terminals are all single characters.*

```
public class SimpleParser {
  final String input;
  SimpleParser(String input) {
    this.input = input;
  }
  class Result {
    int num; // result calculated so far
    int pos; // input position parsed so far
    Result(int num, int pos) {
      this.num = num;
      this.pos = pos;
    }
  }
  class Fail extends Exception {
    Fail() { super() ; }
    Fail(String s) { super(s) ; }
  }
...
  protected Result add(int pos) throws Fail {
    try {
      Result lhs = this.mul(pos);
      Result op = this.eatChar('+', lhs.pos);
      Result rhs = this.add(op.pos);
      return new Result(lhs.num+rhs.num, rhs.pos);
    } catch(Fail ex) { }
    return this.mul(pos);
  }
...
```

Parsing “6*(3+4)”

Add ← Mul + Add / Mul

Mul ← Prim * Mul / Prim

Prim ← (Add) / Dec

Dec ← 0 / 1 / … / 9

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
```

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
```

```
[ ... ]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char +
Add <- Mul [BACKTRACK]
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char )
Eof
312 steps
6*(3+4) -> 42
```

Memoized parsing: Packrat Parsers

> Formally developed by Birman in 1970s

By memoizing parsing results, we avoid having to recalculate partially successful parses.

```
public class SimplePackrat extends SimpleParser {
  Hashtable<Integer,Result>[] hash;
  final int ADD = 0;
  final int MUL = 1;
  final int PRIM = 2;
  final int HASHES = 3;

  SimplePackrat (String input) {
    super(input);
    hash = new Hashtable[HASHES];
    for (int i=0; i<hash.length; i++) {
      hash[i] = new Hashtable<Integer,Result>();
    }
  }

  protected Result add(int pos) throws Fail {
    if (!hash[ADD].containsKey(pos)) {
      hash[ADD].put(pos, super.add(pos));
    }
    return hash[ADD].get(pos);
  }
...
}
```

Memoized parsing “6*(3+4)”

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
```

```
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
Char +
Add <- Mul [BACKTRACK]
MUL -- retrieving hashed result
Char )
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
Char +
Add <- Mul [BACKTRACK]
MUL -- retrieving hashed result
Eof
56 steps
6*(3+4) -> 42
```

What is Packrat Parsing good for?

> Linear cost
—bounded by size(input) × #(parser rules)

> Recognizes strictly larger class of languages than deterministic parsing algorithms (LL(k), LR(k))

> Good for scannerless parsing
—fine-grained tokens, unlimited lookahead

http://www.brynosaurus.com/pub/lang/packrat-icfp02-slides.pdf

Scannerless Parsing

- Traditional linear-time parsers have fixed lookahead
  - —With unlimited lookahead, don’t need separate lexical analysis!
- Scannerless parsing enables unified grammar for entire language
  - —Can express grammars for mixed languages with different lexemes!

What is Packrat Parsing *not* good for?

> General CFG parsing (ambiguous grammars)
  —produces at most one result

> Parsing highly "stateful" syntax (C, C++)
  —memoization depends on statelessness

> Parsing in minimal space
  —LL/LR parsers grow with stack depth, not input size

http://www.brynosaurus.com/pub/lang/packrat-icfp02-slides.pdf

Roadmap

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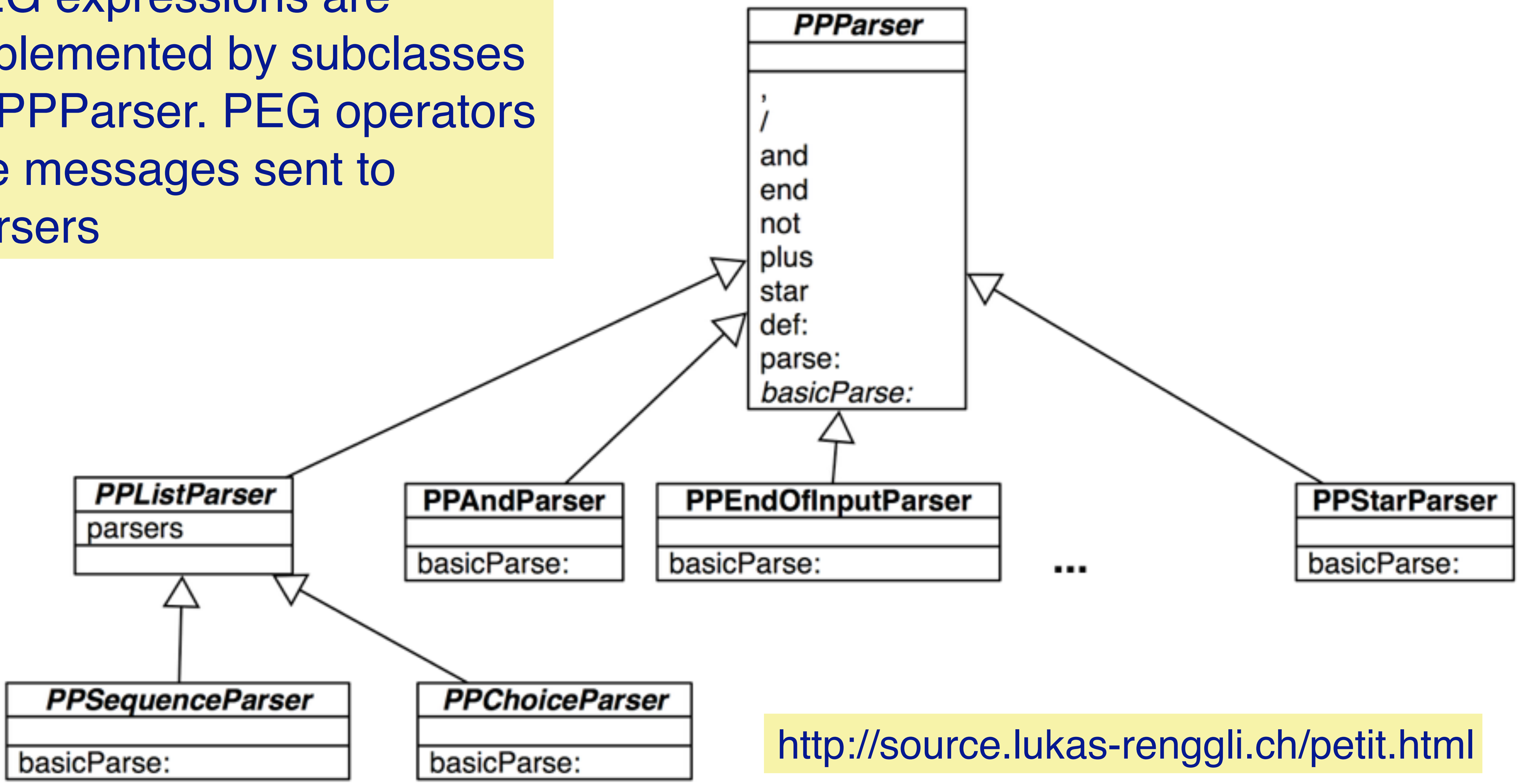
- **Parser Combinators**

Parser Combinators

- Parser combinators in **functional languages** are higher order functions used to build parsers
  - e.g., Parsec, Haskell
- In an **OO language**, a combinator is a (functional) object
  - To build a parser, you simply compose the combinators
  - Combinators can be reused, or specialized with new semantic actions
    - *compiler, pretty printer, syntax highlighter …*
  - e.g., PetitParser, Smalltalk

PetitParser — a PEG parser combinator library for Smalltalk

PEG expressions are implemented by subclasses of PPParser. PEG operators are messages sent to parsers



http://source.lukas-renggli.ch/petit.html

PetitParser example

```
| goal add mul prim dec |

dec := $0 - $9.
add := ( mul, $+ asParser, add )
       / mul.
mul  := ( prim, $* asParser, mul)
       / prim.
prim := ( $( asParser, add, $) asParser)
       / dec.

goal := add end.
goal parse: '6*(3+4)' asParserStream
       ➔ #($6 $* #($( #($3 $+ $4) $)))
```

Add	←	Mul <u>+</u> Add / Mul
Mul	←	Prim <u>*</u> Mul / Prim
Prim	←	<u>(</u> Add <u>)</u> / Dec
Dec	←	<u>0</u> / <u>1</u> / … / <u>9</u>

Semantic actions in PetitParser

```
| goal add mul prim dec |

dec := ($0 - $9)
        ==> [ :token | token asNumber
add := ((mul , $+ asParser , add)
        ==> [ :nodes | nodes first + nodes third ])
        / mul.
mul := ((prim , $* asParser , mul)
        ==> [ :nodes | nodes first + nodes third ])
        / prim.
prim := (($( asParser , add , $) asParser)
        ==> [ :nodes | nodes second ])
        / dec.
goal := add end.

goal parse: '6*(3+4)' asParserStream ➔ 42
```

Add ← Mul <u>+</u> Add / Mul
Mul ← Prim <u>*</u> Mul / Prim
Prim ← <u>(</u> Add <u>)</u> / Dec
Dec ← <u>0</u> / <u>1</u> / … / <u>9</u>

Parser Combinator libraries

> Some OO parser combinator libraries:

- —Java: JParsec
- —C#: NParsec
- —Ruby: Ruby Parsec
- —Python: Pysec
- —*and many more …*

Jparsec — composing a parser from parts

```
public class Calculator {
   …
   static Parser<Double> calculator(Parser<Double> atom) {
      Parser.Reference<Double> ref = Parser.newReference();
      Parser<Double> unit = ref.lazy().between(term("("), term(")")).or(atom);
      Parser<Double> parser = new OperatorTable<Double>()
            .infixl(op("+", BinaryOperator.PLUS), 10)
            .infixl(op("-", BinaryOperator.MINUS), 10)
            .infixl(op("*", BinaryOperator.MUL).or(WHITESPACE_MUL), 20)
            .infixl(op("/", BinaryOperator.DIV), 20)
            .prefix(op("-", UnaryOperator.NEG), 30).build(unit);
      ref.set(parser);
      return parser;
   }

   public static final Parser<Double> CALCULATOR = calculator(NUMBER).from(
         TOKENIZER, IGNORED);
}
```

http://jparsec.codehaus.org/jparsec2+Tutorial

What you should know!

- ✎ *Is a CFG a language recognizer or a language generator? What are the practical implications of this?*
- ✎ *How are PEGs defined?*
- ✎ *How do PEGs differ from CFGs?*
- ✎ *What problem do PEGs solve?*
- ✎ *How does memoization aid backtracking parsers?*
- ✎ *What are scannerless parsers? What are they good for?*
- ✎ *How can parser combinators be implemented as objects?*

Can you answer these questions?

- *Why is it critical for PEGs that parsing functions be stateless?*
- *Why do PEG parsers have unlimited lookahead?*
- *Why are PEGs and packrat parsers well suited to functional programming languages?*
- *What kinds of languages are scannerless parsers good for? When are they inappropriate?*