EECS 321
Programming Languages

Winter 2010

Instructor: **Robby Findler**

Course Details

`http://www.eecs.northwestern.edu/~robby/courses/321-2011-winter/`

(or google "findler" and follow the links)

Programming Language Concepts

This course teaches concepts in two ways:

By implementing **interpreters**

- new concept ⇒ new interpreter

By using **Racket** and variants

- we don't assume that you already know Racket

Interpreters vs Compilers

An ***interpreter*** takes a program and produces a result

- DrRacket
- x86 processor
- desktop calculator
- **`bash`**
- Algebra student

Interpreters vs Compilers

An ***interpreter*** takes a program and produces a result

- DrRacket
- x86 processor
- desktop calculator
- **`bash`**
- Algebra student

A ***compiler*** takes a program and produces a program

- DrRacket
- x86 processor
- **`gcc`**
- **`javac`**

Interpreters vs Compilers

An ***interpreter*** takes a program and produces a result

- DrRacket
- x86 processor
- desktop calculator
- **`bash`**
- Algebra student

> Good for understanding program behavior, easy to implement

A ***compiler*** takes a program and produces a program

- DrRacket
- x86 processor
- **`gcc`**
- **`javac`**

> Good for speed, more complex (come back next quarter)

Interpreters vs Compilers

An ***interpreter*** takes a program and produces a result

- DrRacket
- x86 processor
- desktop calculator
- **`bash`**
- Algebra student

Good for understanding program behavior, easy to implement

A ***compiler*** takes a program and produces a program

- DrRacket
- x86 processor
- **`gcc`**
- **`javac`**

Good for speed, more complex (come back next quarter)

So, what's a ***program***?

A Grammar for Algebra Programs

A grammar of Algebra in ***BNF*** (Backus-Naur Form):

⟨prog⟩	::=	⟨defn⟩* ⟨expr⟩
⟨defn⟩	::=	⟨id⟩(⟨id⟩) = ⟨expr⟩
⟨expr⟩	::=	(⟨expr⟩ + ⟨expr⟩)
	|	(⟨expr⟩ - ⟨expr⟩)
	|	⟨id⟩(⟨expr⟩)
	|	⟨id⟩
	|	⟨num⟩
⟨id⟩	::=	a variable name: **f**, **x**, **y**, **z**, ...
⟨num⟩	::=	a number: 1, 42, 17, ...

A Grammar for Algebra Programs

A grammar of Algebra in ***BNF*** (Backus-Naur Form):

$$
\begin{array}{lcl}
\langle \text{prog} \rangle & ::= & \langle \text{defn} \rangle * \ \langle \text{expr} \rangle \\
\langle \text{defn} \rangle & ::= & \langle \text{id} \rangle(\langle \text{id} \rangle) = \langle \text{expr} \rangle \\
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle \\
\langle \text{id} \rangle & ::= & \text{a variable name: } \mathbf{f}, \mathbf{x}, \mathbf{y}, \mathbf{z}, \ldots \\
\langle \text{num} \rangle & ::= & \text{a number: } 1, 42, 17, \ldots
\end{array}
$$

Each ***meta-variable***, such as $\langle \text{prog} \rangle$, defines a set

Using a BNF Grammar

$\langle \text{id} \rangle$ ::= a variable name: **f**, **x**, **y**, **z**, ...

$\langle \text{num} \rangle$ ::= a number: 1, 42, 17, ...

The set $\langle \text{id} \rangle$ is the set of all variable names

The set $\langle \text{num} \rangle$ is the set of all numbers

Using a BNF Grammar

$\langle$id$\rangle$ ::= a variable name: **f**, **x**, **y**, **z**, ...

$\langle$num$\rangle$ ::= a number: 1, 42, 17, ...

The set $\langle$id$\rangle$ is the set of all variable names

The set $\langle$num$\rangle$ is the set of all numbers

To make an example member of $\langle$num$\rangle$, simply pick an element from the set

Using a BNF Grammar

$\langle \text{id} \rangle$ ::= a variable name: **f**, **x**, **y**, **z**, ...

$\langle \text{num} \rangle$ ::= a number: 1, 42, 17, ...

The set $\langle \text{id} \rangle$ is the set of all variable names

The set $\langle \text{num} \rangle$ is the set of all numbers

To make an example member of $\langle \text{num} \rangle$, simply pick an element from the set

$$2 \in \langle \text{num} \rangle$$

$$298 \in \langle \text{num} \rangle$$

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle
\end{array}
$$

The set $\langle \text{expr} \rangle$ is defined in terms of other sets

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle\text{expr}\rangle & ::= & (\langle\text{expr}\rangle + \langle\text{expr}\rangle) \\
 & | & (\langle\text{expr}\rangle - \langle\text{expr}\rangle) \\
 & | & \langle\text{id}\rangle(\langle\text{expr}\rangle) \\
 & | & \langle\text{id}\rangle \\
 & | & \langle\text{num}\rangle
\end{array}
$$

To make an example ⟨expr⟩:

- choose one case in the grammar
- pick an example for each meta-variable
- combine the examples with literal text

Using a BNF Grammar

⟨expr⟩ ::= (⟨expr⟩ + ⟨expr⟩)
| (⟨expr⟩ - ⟨expr⟩)
| ⟨id⟩(⟨expr⟩)
| ⟨id⟩
| ⟨num⟩

To make an example ⟨expr⟩:

- choose one case in the grammar
- pick an example for each meta-variable
- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

$$7 \in \langle \text{num} \rangle$$

- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
& | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle \\
& | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

$$7 \in \langle \text{num} \rangle$$

- combine the examples with literal text

$$7 \in \langle \text{expr} \rangle$$

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle
\end{array}
$$

To make an example ⟨expr⟩:

- choose one case in the grammar
- pick an example for each meta-variable
- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
& | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle \\
& | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

$$\mathbf{f} \in \langle \text{id} \rangle$$

- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

  $\mathbf{f} \in \langle \text{id} \rangle \qquad 7 \in \langle \text{expr} \rangle$

- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{rcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
& | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle \\
& | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

  $\mathbf{f} \in \langle \text{id} \rangle \qquad 7 \in \langle \text{expr} \rangle$

- combine the examples with literal text

  $\mathbf{f}(7) \in \langle \text{expr} \rangle$

Using a BNF Grammar

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
 & | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
 & | & \langle \text{id} \rangle \\
 & | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

  $\mathbf{f} \in \langle \text{id} \rangle$ $\qquad$ $\mathbf{f}(7) \in \langle \text{expr} \rangle$

- combine the examples with literal text

Using a BNF Grammar

$$
\begin{array}{rcl}
\langle \text{expr} \rangle & ::= & (\langle \text{expr} \rangle + \langle \text{expr} \rangle) \\
& | & (\langle \text{expr} \rangle - \langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle(\langle \text{expr} \rangle) \\
& | & \langle \text{id} \rangle \\
& | & \langle \text{num} \rangle
\end{array}
$$

To make an example $\langle \text{expr} \rangle$:

- choose one case in the grammar
- pick an example for each meta-variable

$$\mathbf{f} \in \langle \text{id} \rangle \qquad\qquad \mathbf{f}(7) \in \langle \text{expr} \rangle$$

- combine the examples with literal text

$$\mathbf{f}(\mathbf{f}(7)) \in \langle \text{expr} \rangle$$

Using a BNF Grammar

$$\langle \text{prog} \rangle \quad ::= \quad \langle \text{defn} \rangle * \ \langle \text{expr} \rangle$$

$$\langle \text{defn} \rangle \quad ::= \quad \langle \text{id} \rangle (\langle \text{id} \rangle) = \langle \text{expr} \rangle$$

$$\mathbf{f}(\mathbf{x}) = (\mathbf{x} + 1) \in \langle \text{defn} \rangle$$

Using a BNF Grammar

$$\langle\text{prog}\rangle \quad ::= \quad \langle\text{defn}\rangle^{*} \ \langle\text{expr}\rangle$$

$$\langle\text{defn}\rangle \quad ::= \quad \langle\text{id}\rangle(\langle\text{id}\rangle) = \langle\text{expr}\rangle$$

$$\mathbf{f}(\mathbf{x}) = (\mathbf{x} + 1) \in \langle\text{defn}\rangle$$

To make a $\langle\text{prog}\rangle$ pick some number of $\langle\text{defn}\rangle$s

$$(\mathbf{x} + \mathbf{y}) \in \langle\text{prog}\rangle$$

$$\left.\begin{array}{l}\mathbf{f}(\mathbf{x}) = (\mathbf{x} + 1) \\ \mathbf{g}(\mathbf{y}) = \mathbf{f}((\mathbf{y} - 2)) \\ \mathbf{g}(7)\end{array}\right. \in \langle\text{prog}\rangle$$

Programming Language

A ***programming language*** is defined by

- a grammar for programs
- rules for evaluating any program to produce a result

Programming Language

A ***programming language*** is defined by

- a grammar for programs
- rules for evaluating any program to produce a result

For example, Algebra evaluation is defined in terms of evaluation steps:

$$(2 + (7 - 4)) \quad \rightarrow \quad (2 + 3) \quad \rightarrow \quad 5$$

Programming Language

A ***programming language*** is defined by

- a grammar for programs
- rules for evaluating any program to produce a result

For example, Algebra evaluation is defined in terms of evaluation steps:

$$\mathbf{f}(\mathbf{x}) = (\mathbf{x} + 1)$$

$$\mathbf{f}(10) \quad \rightarrow \quad (10 + 1) \quad \rightarrow \quad 11$$

Evaluation

- Evaluation $\rightarrow$ is defined by a set of pattern-matching rules:

$$(2 + (7 - 4)) \quad \rightarrow \quad (2 + 3)$$

due to the pattern rule

$$\ldots\ (7 - 4)\ \ldots \quad \rightarrow \quad \ldots\ 3\ \ldots$$

Evaluation

- Evaluation $\longrightarrow$ is defined by a set of pattern-matching rules:

$$\mathbf{f}(\mathbf{x}) = (\mathbf{x} + 1)$$

$$\mathbf{f}(10) \quad \longrightarrow \quad (10 + 1)$$

due to the pattern rule

$$\ldots \langle \text{id} \rangle_1 (\langle \text{id} \rangle_2) = \langle \text{expr} \rangle_1 \ldots$$

$$\ldots \langle \text{id} \rangle_1 (\langle \text{expr} \rangle_2) \ldots \quad \longrightarrow \quad \ldots \langle \text{expr} \rangle_3 \ldots$$

where $\langle \text{expr} \rangle_3$ is $\langle \text{expr} \rangle_1$ with $\langle \text{id} \rangle_2$ replaced by $\langle \text{expr} \rangle_2$

Rules for Evaluation

- **Rule 1 -** one pattern

$$\ldots\ \langle \text{id} \rangle_{\mathbf{1}}(\langle \text{id} \rangle_{\mathbf{2}}) = \langle \text{expr} \rangle_{\mathbf{1}}\ \ldots$$

$$\ldots\ \langle \text{id} \rangle_{\mathbf{1}}(\langle \text{expr} \rangle_{\mathbf{2}})\ \ldots \quad \longrightarrow \quad \ldots\ \langle \text{expr} \rangle_{\mathbf{3}}\ \ldots$$

where $\langle \text{expr} \rangle_{\mathbf{3}}$ is $\langle \text{expr} \rangle_{\mathbf{1}}$ with $\langle \text{id} \rangle_{\mathbf{2}}$ replaced by $\langle \text{expr} \rangle_{\mathbf{2}}$

Rules for Evaluation

- **Rule 1 -** one pattern

$$\ldots \langle \text{id} \rangle_1(\langle \text{id} \rangle_2) = \langle \text{expr} \rangle_1 \ldots$$

$$\ldots \langle \text{id} \rangle_1(\langle \text{expr} \rangle_2) \ldots \quad \rightarrow \quad \ldots \langle \text{expr} \rangle_3 \ldots$$

where $\langle \text{expr} \rangle_3$ is $\langle \text{expr} \rangle_1$ with $\langle \text{id} \rangle_2$ replaced by $\langle \text{expr} \rangle_2$

- **Rules 2 -** ∞ special cases

... (0 + 0) ... → ... 0 ...	... (0 - 0) ... → ... 0 ...
... (1 + 0) ... → ... 1 ...	... (1 - 0) ... → ... 1 ...
... (2 + 0) ... → ... 2 ...	... (2 - 0) ... → ... 2 ...
etc.	*etc.*

Rules for Evaluation

- **Rule 1 -** one pattern

$$\ldots \langle \text{id} \rangle_1(\langle \text{id} \rangle_2) = \langle \text{expr} \rangle_1 \ldots$$

$$\ldots \langle \text{id} \rangle_1(\langle \text{expr} \rangle_2) \ldots \quad \rightarrow \quad \ldots \langle \text{expr} \rangle_3 \ldots$$

where $\langle \text{expr} \rangle_3$ is $\langle \text{expr} \rangle_1$ with $\langle \text{id} \rangle_2$ replaced by $\langle \text{expr} \rangle_2$

- **Rules 2 -** ∞ special cases

... (0 + 0) ... → ... 0 ...	... (0 - 0) ... → ... 0 ...
... (1 + 0) ... → ... 1 ...	... (1 - 0) ... → ... 1 ...
... (2 + 0) ... → ... 2 ...	... (2 - 0) ... → ... 2 ...
etc.	*etc.*

When the interpreter is a program instead of an Algebra student, the rules look a little different

HW 1

On the course web page:

Write an interpreter for a small language of string manipulations

Assignment is due **Friday**