

# CMSC 330: Organization of Programming Languages

## Operational Semantics

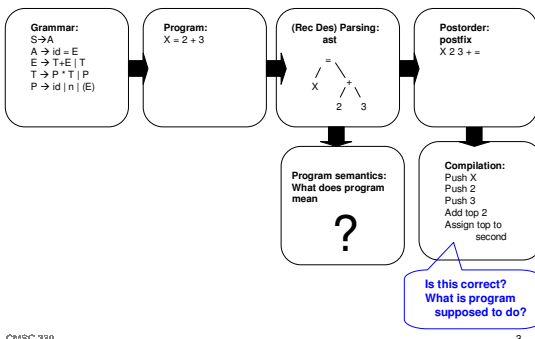
## Introduction

- So far we've looked at regular expressions, automata, and context-free grammars
  - These are ways of defining sets of strings
  - We can use these to describe what programs you can write down in a language
    - (Almost...)
  - I.e., these describe the *syntax* of a language
- What about the *semantics* of a language?
  - What does a program "mean"?

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## Roadmap: Compilation of program



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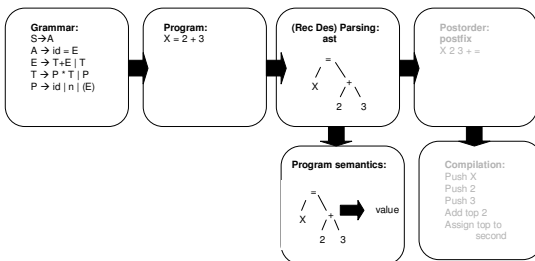
## Operational Semantics

- There are several different kinds of semantics
  - *Denotational*: A program is a mathematical function
  - *Axiomatic*: Develop a logical proof of a program
    - Give predicates that hold when a program (or part) is executed
- We will briefly look at *operational semantics*
  - A program is defined by how you execute it on a mathematical model of a machine
  - Operational semantics are easy to understand
- We will look at a subset of OCaml as an example

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## Roadmap: Semantics of a program



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## Evaluation

- We're going to define a relation  $E \rightarrow v$ 
  - This means "expression  $E$  evaluates to  $v$ "
- So we need a formal way of defining programs and of defining things they may evaluate to
- We'll use grammars to describe each of these
  - One to describe abstract syntax trees  $E$
  - One to describe OCaml values  $v$

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## OCaml Programs

- $E ::= x \mid n \mid \text{true} \mid \text{false} \mid [] \mid \text{if } E \text{ then } E \text{ else } E$   
 $\mid \text{fun } x = E \mid E E$ 
  - $x$  stands for any identifier
  - $n$  stands for any integer
  - $\text{true}$  and  $\text{false}$  stand for the two boolean values
  - $[]$  is the empty list
  - Using  $=$  in fun instead of  $\rightarrow$  to avoid some confusion later

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## Values

- $v ::= n \mid \text{true} \mid \text{false} \mid [] \mid v::v$ 
  - $n$  is an integer (*not* a string corresp. to an integer)
    - Same idea for  $\text{true}$ ,  $\text{false}$ ,  $[]$
  - $v1::v2$  is the pair with  $v1$  and  $v2$ 
    - This will be used to build up lists
    - Notice: nothing yet requires  $v2$  to be a list
  - **Important:** Be sure to understand the difference between *program text*  $S$  and *mathematical objects*  $v$ .
    - E.g., the text  $3$  evaluates to the mathematical number  $3$
  - To help, we'll use different colors and italics
    - This is usually not done, and it's up to the reader to remember which is which

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## Grammars for Trees

- We're just using grammars to describe trees

$E ::= x \mid n \mid \text{true} \mid \text{false} \mid [] \mid \text{if } E \text{ then } E \text{ else } E$   
 $\mid \text{fun } x = E \mid E E$

$v ::= n \mid \text{true} \mid \text{false} \mid [] \mid v::v$

Given a program, we saw previously how to convert it to an ast (e.g., recursive descent parsing)

```
type ast =
  | Id of string
  | Num of int
  | Bool of bool
  | Nil
  | If of ast * ast * ast
  | Fun of string * ast
  | App of ast * ast
```

```
type value =
  | Val_Num of int
  | Val_Bool of bool
  | Val_Nil
  | Val_Pair of value *
    value
```

Goal: For any ast, we want an operational rule to obtain a value that represents the execution of ast

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## Operational Semantics Rules

$n \rightarrow n$   
 $\text{true} \rightarrow \text{true}$   
 $\text{false} \rightarrow \text{false}$   
 $[] \rightarrow []$

- Each basic entity evaluates to the corresponding value

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## Operational Semantics Rules (cont'd)

- How about built-in functions?

$(+) n m \rightarrow n + m$

- We're applying the  $+$  function
  - (we put parens around it because it's not in infix notation; will skip this from now on)
  - Ignore currying for the moment, and pretend we have multi-argument functions
- On the right-hand side, we're computing the mathematical sum; the left-hand side is source code
- But what about  $+(+34)5$ ?
  - We need recursion

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## Rules with Hypotheses

- To evaluate  $+ E_1 E_2$ , we need to evaluate  $E_1$ , then evaluate  $E_2$ , then add the results
  - This is call-by-value

$$\frac{E_1 \rightarrow n \quad E_2 \rightarrow m}{+ E_1 E_2 \rightarrow n + m}$$

- This is a "natural deduction" style rule
- It says that if the *hypotheses* above the line hold, then the *conclusion* below the line holds
  - i.e., if  $E_1$  executes to value  $n$  and if  $E_2$  executes to value  $m$ , then  $+ E_1 E_2$  executes to value  $n+m$

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## Error Cases

$$\frac{E_1 \rightarrow n \quad E_2 \rightarrow m}{+ E_1 E_2 \rightarrow n + m}$$

- Because we wrote  $n, m$  in the hypothesis, we mean that they must be integers
- But what if  $E_1$  and  $E_2$  aren't integers?
  - E.g., what if we write `+ false true`?
  - It can be parsed, but we can't execute it
- We will have no rule that covers such a case
  - Convention: If there is not rule to cover a case, then the expression is erroneous
  - A program that evaluates to a stuck expression produces a run time error in practice

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## Trees of Semantic Rules

- When we apply rules to an expression, we actually get a tree
  - Corresponds to the recursive evaluation procedure
    - For example: `+(+34)5`

$$\frac{\frac{3 \rightarrow 3 \quad 4 \rightarrow 4}{(+34) \rightarrow 7} \quad 5 \rightarrow 5}{+(+34)5 \rightarrow 12}$$

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## Rules for If

$$\frac{E_1 \rightarrow \text{true} \quad E_2 \rightarrow v}{\text{if } E_1 \text{ then } E_2 \text{ else } E_3 \rightarrow v}$$

$$\frac{E_1 \rightarrow \text{false} \quad E_3 \rightarrow v}{\text{if } E_1 \text{ then } E_2 \text{ else } E_3 \rightarrow v}$$

- Examples
  - `if false then 3 else 4` → 4
  - `if true then 3 else 4` → 3
- Notice that only one branch is evaluated

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## Rule for ::

$$\frac{E_1 \rightarrow v_1 \quad E_2 \rightarrow v_2}{:: E_1 E_2 \rightarrow v_1 :: v_2}$$

- So `::` allocates a pair in memory
- Are there any conditions on  $E_1$  and  $E_2$ ?
  - No! We will allow  $E_2$  to be anything
  - OCaml's type system will disallow non-lists

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## Rules for Hd and Tl

$$\frac{E \rightarrow v_1 :: v_2}{\text{hd } E \rightarrow v_1}$$

$$\frac{E \rightarrow v_1 :: v_2}{\text{tl } E \rightarrow v_2}$$

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## Rules for Identifiers

$$\frac{}{x \rightarrow ???}$$

- Let's assume for now that the only identifiers are parameter names
  - Ex. `(fun x = + x 3) 4`
  - When we see  $x$  in the body, we need to look it up
  - So we need to keep some sort of *environment*
    - This will be a map from identifiers to values

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## Semantics with Environments

- Extend rules to the form  $A; E \rightarrow v$ 
  - Means in environment  $A$ , the program text  $E$  evaluates to  $v$
- Notation:
  - We write  $\bullet$  for the empty environment
  - We write  $A(x)$  for the value that  $x$  maps to in  $A$
  - We write  $A, x:v$  for the same environment as  $A$ , except  $x$  is now  $v$ 
    - $x$  might or might not have mapped to anything in  $A$
  - We write  $A, A'$  for the environment with the bindings of  $A'$  added to and overriding the bindings of  $A$
  - The empty environment can be omitted when things are clear, and in adding other bindings to an empty environment we can write just those bindings if things are clear

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## Rules for Identifiers and Application

$$A; x \rightarrow A(x)$$

no hypothesis means "in all cases"

$$A; E_2 \rightarrow v \quad A, x:v; E_1 \rightarrow v'$$

$$A; (\text{fun } x = E_1) E_2 \rightarrow v'$$

- To evaluate a user-defined function applied to an argument:
  - Evaluate the argument (call-by-value)
  - Evaluate the function body in an environment in which the formal parameter is bound to the actual argument
  - Return the result

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## Example: $(\text{fun } x = + x 3) 4 = ?$

$$\begin{array}{l} \bullet, x:4; x \rightarrow 4 \quad \bullet, x:4; 3 \rightarrow 3 \\ \bullet; 4 \rightarrow 4 \quad \bullet, x:4; + x 3 \rightarrow 7 \\ \hline \bullet; (\text{fun } x = + x 3) 4 \rightarrow 7 \end{array}$$

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## Nested Functions

- This works for cases of nested functions
  - ...as long as they are fully applied
- But what about the true higher-order cases?
  - Passing functions as arguments, and returning functions as results
  - We need closures to handle this case
  - ...and a closure was just a function and an environment
  - We already have notation around for writing both parts

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## Closures

- Formally, we add closures  $(A, \lambda x.E)$  to values
  - $A$  is the environment in which the closure was created
  - $x$  is the parameter name
  - $E$  is the source code for the body
- $\lambda x$  will be discussed next time. Means a binding of  $x$  in  $E$ .
- $v ::= n \mid \text{true} \mid \text{false} \mid [] \mid v::v \mid (A, \lambda x.E)$

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## Revised Rule for Lambda

$$A; \text{fun } x = E \rightarrow (A, \lambda x.E)$$

- To evaluate a function definition, create a closure when the function is created
  - Notice that we don't look inside the function body

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## Revised Rule for Application

$$\frac{A; E_1 \rightarrow (A', \lambda x. E) \quad A; E_2 \rightarrow v \quad A', x:v; E \rightarrow v'}{A; (E_1 E_2) \rightarrow v'}$$

- To apply something to an argument:
  - Evaluate it to produce a closure
  - Evaluate the argument (call-by-value)
  - Evaluate the body of the closure, in
    - The current environment, extended with the closure's environment, extended with the binding for the parameter

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## Example

$$\begin{aligned} \bullet; (\text{fun } x = (\text{fun } y = + x y)) &\rightarrow (\bullet, \lambda x. (\text{fun } y = + x y)) \\ &\quad \bullet; 3 \rightarrow 3 \\ x:3; (\text{fun } y = + x y) &\rightarrow (x:3, \lambda y. (+ x y)) \\ \bullet; (\text{fun } x = (\text{fun } y = + x y)) \ 3 &\rightarrow (x:3, \lambda y. (+ x y)) \end{aligned}$$

Let <previous> = (fun x = (fun y = + x y)) 3

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## Example (cont'd)

$$\begin{aligned} \bullet; \text{<previous>} &\rightarrow (x:3, \lambda y. (+ x y)) \\ &\quad \bullet; 4 \rightarrow 4 \\ x:3, y:4; (+ x y) &\rightarrow 7 \\ \bullet; (\text{<previous>} \ 4) &\rightarrow 7 \end{aligned}$$

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## Why Did We Do This? (cont'd)

- Operational semantics are useful for
  - Describing languages
    - Not just OCaml! It's pretty hard to describe a big language like C or Java, but we can at least describe the core components of the language
  - Giving a *precise* specification of how they work
    - Look in any language standard – they tend to be vague in many places and leave things undefined
  - Reasoning about programs
    - We can actually prove that programs do something or don't do something, because we have a precise definition of how they work

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