Programming Languages and Compilers (CS 421)

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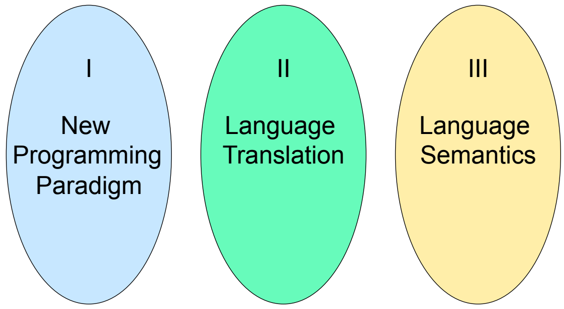
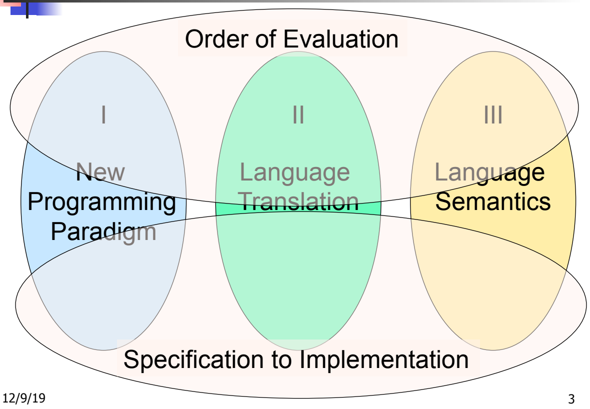
Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Programming Languages & Compilers

Three Main Topics of the Course

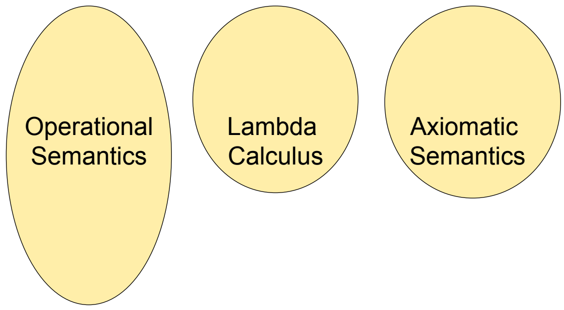


Programming Languages & Compilers

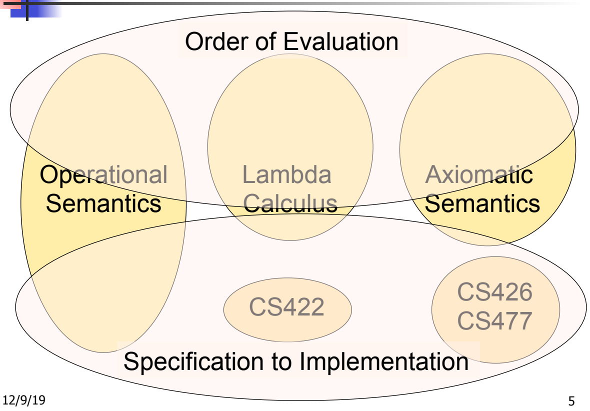


Programming Languages & Compilers

III : Language Semantics



Programming Languages & Compilers



Semantics

- Expresses the meaning of syntax
- Static semantics
  - Meaning based only on the form of the expression without executing it
  - Usually restricted to type checking / type inference

Dynamic semantics

- Method of describing meaning of executing a program
- Several different types:
  - Operational Semantics
  - Axiomatic Semantics
  - Denotational Semantics

Dynamic Semantics

- Different languages better suited to different types of semantics
- Different types of semantics serve different purposes

Operational Semantics

- Start with a simple notion of machine
- Describe how to execute (implement) programs of language on virtual machine, by describing how to execute each program statement (ie, following the *structure* of the program)
- Meaning of program is how its execution changes the state of the machine
- Useful as basis for implementations

Axiomatic Semantics

- Also called Floyd-Hoare Logic
- Based on formal logic (first order predicate calculus)
- Axiomatic Semantics is a logical system built from *axioms* and *inference rules*
- Mainly suited to simple imperative programming languages

Axiomatic Semantics

- Used to formally prove a property (*post-condition*) of the *state* (the values of the program variables) after the execution of program, assuming another property (*pre-condition*) of the state before execution
- Written :

  {Precondition} Program {Postcondition}
- Source of idea of *loop invariant*

Denotational Semantics

- Construct a function $\mathcal{M}$ assigning a mathematical meaning to each program construct
- Lambda calculus often used as the range of the meaning function
- Meaning function is compositional: meaning of construct built from meaning of parts
- Useful for proving properties of programs

Natural Semantics

- Aka Structural Operational Semantics, aka "Big Step Semantics"
- Provide value for a program by rules and derivations, similar to type derivations
- Rule conclusions look like

$$(C, m) \Downarrow m'$$

or

$$(E, m) \Downarrow v$$

Simple Imperative Programming Language

- $I \in$ *Identifiers*
- $N \in$ *Numerals*
- B ::= true | false | B & B | B or B | not B | E < E | E = E
- E ::= N | I | E + E | E * E | E - E | - E
- C ::= skip | C;C | I := E | if B then C else C fi | while B do C od

Natural Semantics of Atomic Expressions

- Identifiers: $(I,m) \Downarrow m(I)$
- Numerals are values: $(N,m) \Downarrow N$
- Booleans: $(\text{true},m) \Downarrow \text{true}$
  $(\text{false},m) \Downarrow \text{false}$

Booleans:

$$\frac{(B, m) \Downarrow \text{false}}{(B \,\&\, B', m) \Downarrow \text{false}} \qquad \frac{(B, m) \Downarrow \text{true} \quad (B', m) \Downarrow b}{(B \,\&\, B', m) \Downarrow b}$$

$$\frac{(B, m) \Downarrow \text{true}}{(B \text{ or } B', m) \Downarrow \text{true}} \qquad \frac{(B, m) \Downarrow \text{false} \quad (B', m) \Downarrow b}{(B \text{ or } B', m) \Downarrow b}$$

$$\frac{(B, m) \Downarrow \text{true}}{(\text{not } B, m) \Downarrow \text{false}} \qquad \frac{(B, m) \Downarrow \text{false}}{(\text{not } B, m) \Downarrow \text{true}}$$

Relations

$$\frac{(E, m) \Downarrow U \quad (E', m) \Downarrow V \quad U \sim V = b}{(E \sim E', m) \Downarrow b}$$

- By $U \sim V = b$, we mean does (the meaning of) the relation $\sim$ hold on the meaning of U and V
- May be specified by a mathematical expression/equation or rules matching U and V

Arithmetic Expressions

$$\frac{(E, m) \Downarrow U \quad (E', m) \Downarrow V \quad U \text{ op } V = N}{(E \text{ op } E', m) \Downarrow N}$$

where N is the specified value for U *op* V

Commands

Skip: (skip, m) $\Downarrow$ m

Assignment:

$$\frac{(E,m) \Downarrow V}{(I{:=}E,m) \Downarrow m[I \texttt{<--} V]}$$

Sequencing:

$$\frac{(C,m) \Downarrow m' \quad (C',m') \Downarrow m''}{(C;C',\, m) \Downarrow m''}$$

If Then Else Command

$$\frac{(B,m) \Downarrow \text{true} \quad (C,m) \Downarrow m'}{(\text{if } B \text{ then } C \text{ else } C' \text{ fi},\, m) \Downarrow m'}$$

$$\frac{(B,m) \Downarrow \text{false} \quad (C',m) \Downarrow m'}{(\text{if } B \text{ then } C \text{ else } C' \text{ fi},\, m) \Downarrow m'}$$

While Command

$$\frac{(B,m) \Downarrow \text{false}}{(\text{while } B \text{ do } C \text{ od},\, m) \Downarrow m}$$

$$\frac{(B,m)\Downarrow\text{true} \quad (C,m)\Downarrow m' \quad (\text{while } B \text{ do } C \text{ od},\, m')\Downarrow m''}{(\text{while } B \text{ do } C \text{ od},\, m) \Downarrow m''}$$

Example: If Then Else Rule

$$\frac{}{\begin{array}{c}(\text{if } x > 5 \text{ then } y{:=}\ 2 + 3 \text{ else } y{:=}3 + 4 \text{ fi},\\ \{x \texttt{->} 7\}) \Downarrow ?\end{array}}$$

Example: If Then Else Rule

$$\frac{\dfrac{}{(x > 5,\ \{x \texttt{->} 7\})\Downarrow ?}}{\begin{array}{c}(\text{if } x > 5 \text{ then } y{:=}\ 2 + 3 \text{ else } y{:=}3 + 4 \text{ fi},\\ \{x \texttt{->} 7\}) \Downarrow\ ?\end{array}}$$

Example: Arith Relation

$$\frac{\dfrac{? > ? = ? \qquad}{(x,\{x\texttt{->}7\})\Downarrow ? \quad (5,\{x\texttt{->}7\})\Downarrow ?}}{\dfrac{(x > 5,\ \{x \texttt{->} 7\})\Downarrow ?}{\begin{array}{c}(\text{if } x > 5 \text{ then } y{:=}\ 2 + 3 \text{ else } y{:=}3 + 4 \text{ fi},\\ \{x \texttt{->} 7\}) \Downarrow ?\end{array}}}$$

Example: Identifier(s)

7 > 5 = true
(x,{x->7})⇓7   (5,{x->7})⇓5
(x > 5, {x -> 7})⇓?
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: Arith Relation

7 > 5 = true
(x,{x->7})⇓7   (5,{x->7})⇓5
(x > 5, {x -> 7})⇓true
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: If Then Else Rule

7 > 5 = true
(x,{x->7})⇓7   (5,{x->7})⇓5   (y:= 2 + 3, {x-> 7}
(x > 5, {x -> 7})⇓true   ⇓ ?   .
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: Assignment

7 > 5 = true   (2+3, {x->7})⇓?
(x,{x->7})⇓7   (5,{x->7})⇓5   (y:= 2 + 3, {x-> 7}
(x > 5, {x -> 7})⇓true   ⇓ ?
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: Arith Op

? + ? = ?
(2,{x->7})⇓?   (3,{x->7}) ⇓?
7 > 5 = true   (2+3, {x->7})⇓?
(x,{x->7})⇓7   (5,{x->7})⇓5   (y:= 2 + 3, {x-> 7}
(x > 5, {x -> 7})⇓true   ⇓?   .
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: Numerals

2 + 3 = 5
(2,{x->7})⇓2   (3,{x->7}) ⇓3
7 > 5 = true   (2+3, {x->7})⇓?
(x,{x->7})⇓7   (5,{x->7})⇓5   (y:= 2 + 3, {x-> 7}
(x > 5, {x -> 7})⇓true   ⇓ ?
(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: Arith Op

$$\dfrac{\dfrac{7 > 5 = \text{true}}{\dfrac{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}{(x > 5, \{x \text{->} 7\})\Downarrow \text{true}}} \quad \dfrac{\dfrac{\dfrac{2 + 3 = 5}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{(2+3, \{x\text{->}7\})\Downarrow 5}}{\dfrac{(y{:}= 2 + 3, \{x\text{->} 7\}}{\Downarrow ?}}}{(\text{if } x > 5 \text{ then } y{:}= 2 + 3 \text{ else } y{:}=3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?}$$

Example: Assignment

$$\dfrac{\dfrac{7 > 5 = \text{true}}{\dfrac{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}{(x > 5, \{x \text{->} 7\})\Downarrow \text{true}}} \quad \dfrac{\dfrac{\dfrac{2 + 3 = 5}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{(2+3, \{x\text{->}7\})\Downarrow 5}}{\dfrac{(y{:}= 2 + 3, \{x\text{->} 7\}}{\Downarrow \{x\text{->}7, y\text{->}5\}}}}{(\text{if } x > 5 \text{ then } y{:}= 2 + 3 \text{ else } y{:}=3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?}$$

Example: If Then Else Rule

$$\dfrac{\dfrac{7 > 5 = \text{true}}{\dfrac{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}{(x > 5, \{x \text{->} 7\})\Downarrow \text{true}}} \quad \dfrac{\dfrac{\dfrac{2 + 3 = 5}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{(2+3, \{x\text{->}7\})\Downarrow 5}}{\dfrac{(y{:}= 2 + 3, \{x\text{->} 7\}}{\Downarrow \{x\text{->}7, y\text{->}5\}}}}{(\text{if } x > 5 \text{ then } y{:}= 2 + 3 \text{ else } y{:}=3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow \{x\text{->}7, y\text{->}5\}}$$

Let in Command

$$\dfrac{(E,m) \Downarrow v \quad (C,m[I\text{<-}v]) \Downarrow m'}{(\text{let } I = E \text{ in } C,\ m) \Downarrow m''}$$

Where $m''(y) = m'(y)$ for $y \neq I$ and $m''(I) = m(I)$ if $m(I)$ is defined, and $m''(I)$ is undefined otherwise

Example

$$\dfrac{(5,\{x\text{->}17\}) \Downarrow 5 \quad \dfrac{\dfrac{(x,\{x\text{->}5\}) \Downarrow 5 \quad (3,\{x\text{->}5\}) \Downarrow 3}{(x+3,\{x\text{->}5\}) \Downarrow 8}}{(x{:}=x+3,\{x\text{->}5\}) \Downarrow \{x\text{->}8\}}}{(\text{let } x = 5 \text{ in } (x{:}=x+3), \{x \text{->} 17\}) \Downarrow ?}$$

Example

$$\dfrac{(5,\{x\text{->}17\}) \Downarrow 5 \quad \dfrac{\dfrac{(x,\{x\text{->}5\}) \Downarrow 5 \quad (3,\{x\text{->}5\}) \Downarrow 3}{(x+3,\{x\text{->}5\}) \Downarrow 8}}{(x{:}=x+3,\{x\text{->}5\}) \Downarrow \{x\text{->}8\}}}{(\text{let } x = 5 \text{ in } (x{:}=x+3), \{x \text{->} 17\}) \Downarrow \{x\text{->}17\}}$$

Comment

- Simple Imperative Programming Language introduces variables *implicitly* through assignment
- The let-in command introduces scoped variables *explictly*
- Clash of constructs apparent in awkward semantics

Interpretation Versus Compilation

- A **compiler** from language L1 to language L2 is a program that takes an L1 program and for each piece of code in L1 generates a piece of code in L2 of same meaning
- An **interpreter** of L1 in L2 is an L2 program that executes the meaning of a given L1 program
- Compiler would examine the body of a loop once; an interpreter would examine it every time the loop was executed

Interpreter

- An *Interpreter* represents the operational semantics of a language L1 (source language) in the language of implementation L2 (target language)
- Built incrementally
  - Start with literals
  - Variables
  - Primitive operations
  - Evaluation of expressions
  - Evaluation of commands/declarations

Interpreter

- Takes abstract syntax trees as input
  - In simple cases could be just strings
- One procedure for each syntactic category (nonterminal)
  - eg one for expressions, another for commands
- If Natural semantics used, tells how to compute final value from code
- If Transition semantics used, tells how to compute next "state"
  - To get final value, put in a loop

Natural Semantics Example

- compute_exp (Var(v), m) = look_up v m
- compute_exp (Int(n), _) = Num (n)
- …
- compute_com(IfExp(b,c1,c2),m) =

  if compute_exp (b,m) = Bool(true)
  then compute_com (c1,m)
  else compute_com (c2,m)

Natural Semantics Example

- compute_com(While(b,c), m) =

  if compute_exp (b,m) = Bool(false)
  then m
  else compute_com
  (While(b,c), compute_com(c,m))

- May fail to terminate - exceed stack limits
- Returns no useful information then

Transition Semantics

- Form of operational semantics
- Describes how each program construct transforms machine state by *transitions*
- Rules look like
  (C, *m*) --> (C', *m'*) or (C,*m*) --> *m'*
- *C, C'* is code remaining to be executed
- m, m' represent the state/store/memory/ environment
  - Partial mapping from identifiers to values
  - Sometimes *m* (or *C*) not needed
- Indicates exactly one step of computation

Expressions and Values

- *C, C'* used for commands; *E, E' for* expressions; *U,V* for values
- Special class of expressions designated as *values*
  - Eg 2, 3 are values, but 2+3 is only an expression
- Memory only holds values
  - Other possibilities exist

Evaluation Semantics

- Transitions successfully stops when E/*C* is a value/memory
- Evaluation fails if no transition possible, but not at value/memory
- Value/memory is the final *meaning* of original expression/command (in the given state)
- Coarse semantics: final value / memory
- More fine grained: whole transition sequence

Simple Imperative Programming Language

- *I* ∈ *Identifiers*
- *N* ∈ *Numerals*
- *B* ::= true | false | *B* & *B* | *B* or *B* | not *B* | *E* < *E* | *E* = *E*
- *E::= N | I | E + E | E * E | E - E | - E*
- C::= skip | *C*;*C* | *I* ::= *E*
  | if *B* then *C* else *C* fi | while *B* do *C* od

Transitions for Expressions

- Numerals are values
- Boolean values = {true, false}
- Identifiers: (*I*,*m*) --> (*m*(*I*), *m*)

Boolean Operations:

- Operators: (short-circuit)

(false & *B*, *m*) --> (false,*m*)
(true & *B*, *m*) --> (*B*,*m*)

$$\frac{(B,\ m) \dashrightarrow (B'',\ m)}{(B \,\&\, B',\ m) \dashrightarrow (B'' \,\&\, B',\ m)}$$

(true or *B*, *m*) --> (true,*m*)
(false or *B*, *m*) --> (*B*,*m*)

$$\frac{(B,\ m) \dashrightarrow (B'',\ m)}{(B \text{ or } B',\ m) \dashrightarrow (B'' \text{ or } B',m)}$$

(not true, m) --> (false,*m*)
(not false, m) --> (true,*m*)

$$\frac{(B,\ m) \dashrightarrow (B',\ m)}{(\text{not } B,\ m) \dashrightarrow (\text{not } B',\ m)}$$

Relations

$$\frac{(E, m) \dashrightarrow (E'', m)}{(E \sim E', m) \dashrightarrow (E'' \sim E', m)}$$

$$\frac{(E, m) \dashrightarrow (E', m)}{(V \sim E, m) \dashrightarrow (V \sim E', m)}$$

($U \sim V$, m) --> (true,m) or (false,m) depending on whether $U \sim V$ holds or not

Arithmetic Expressions

$$\frac{(E, m) \dashrightarrow (E'', m)}{(E \; op \; E', m) \dashrightarrow (E'' \; op \; E', m)}$$

$$\frac{(E, m) \dashrightarrow (E', m)}{(V \; op \; E, m) \dashrightarrow (V \; op \; E', m)}$$

(U *op* V, m) --> (N,m) where N is the specified value for U *op* V

Commands - in English

- skip means done evaluating
- When evaluating an assignment, evaluate the expression first
- If the expression being assigned is already a value, update the memory with the new value for the identifier
- When evaluating a sequence, work on the first command in the sequence first
- If the first command evaluates to a new memory (ie completes), evaluate remainder with new memory

Commands

(skip, m) --> m

$$\frac{(E, m) \dashrightarrow (E', m)}{(I ::= E, m) \dashrightarrow (I ::= E', m)}$$

(I::=V,m) --> m[I <-- V]

$$\frac{(C, m) \dashrightarrow (C'', m')}{(C;C', m) \dashrightarrow (C'';C', m')} \qquad \frac{(C, m) \dashrightarrow m'}{(C;C', m) \dashrightarrow (C', m')}$$

If Then Else Command - in English

- If the boolean guard in an if_then_else is true, then evaluate the first branch
- If it is false, evaluate the second branch
- If the boolean guard is not a value, then start by evaluating it first.

If Then Else Command

(if true then C else C' fi, m) --> (C, m)

(if false then C else C' fi, m) --> (C', m)

$$\frac{(B, m) \dashrightarrow (B', m)}{(\text{if } B \text{ then } C \text{ else } C' \text{ fi}, m) \dashrightarrow (\text{if } B' \text{ then } C \text{ else } C' \text{ fi}, m)}$$

Wrong! BAD!

(while true do C od, m) -→ (C , m)

(while true do x := 5 od, { x-> 5})

(B, m) → (B′, m)

(while B do C od, m) -→ (while B′ do C od, m)

While Command

(while *B* do *C* od, *m*) -->
(if *B* then *C*; while *B* do *C* od else skip fi, m)

In English: Expand a While into a test of the boolean guard, with the true case being to do the body and then try the while loop again, and the false case being to stop.

Example Evaluation

- First step:

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> ?

Example Evaluation

- First step:

(x > 5, {x -> 7}) --> ?

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> ?

Example Evaluation

- First step:

(x,{x -> 7}) --> (7, {x -> 7})

(x > 5, {x -> 7}) --> ?

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> ?

Example Evaluation

- First step:

(x,{x -> 7}) --> (7, {x -> 7})

(x > 5, {x -> 7}) --> (7 > 5, {x -> 7})

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> ?

Example Evaluation

- First step:

(x,{x -> 7}) --> (7, {x -> 7})

(x > 5, {x -> 7}) --> (7 > 5, {x -> 7})

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> (if 7 > 5 then y:=2 + 3 else y:=3 + 4 fi,
{x -> 7})

Example Evaluation

- Second Step:

(7 > 5, {x -> 7}) --> (true, {x -> 7})

(if 7 > 5 then y:=2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> (if true then y:=2 + 3 else y:=3 + 4 fi,
{x -> 7})

- Third Step:

(if true then y:=2 + 3 else y:=3 + 4 fi, {x -> 7})
-->(y:=2+3, {x->7})

Example Evaluation

- Fourth Step:

(2+3, {x-> 7}) --> (5, {x -> 7})

(y:=2+3, {x->7}) --> (y:=5, {x->7})

- Fifth Step:

(y:=5, {x->7}) --> {y -> 5, x -> 7}

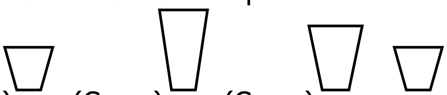
Example Evaluation

- Bottom Line:

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7})
--> (if 7 > 5 then y:=2 + 3 else y:=3 + 4 fi,
{x -> 7})
-->(if true then y:=2 + 3 else y:=3 + 4 fi,
{x -> 7})
-->(y:=2+3, {x->7})
--> (y:=5, {x->7}) --> {y -> 5, x -> 7}

Transition Semantics Evaluation

- A sequence of steps with trees of justification for each step



(C_1,m_1) --> (C_2,m_2) --> (C_3,m_3) --> … --> m

- Let -->* be the transitive closure of -->
- Ie, the smallest transitive relation containing -->

Adding Local Declarations

- Add to expressions:
- *E* ::= … | let *I* = *E* in *E'* | fun *I* -> *E* | *E E'*
- fun *I* -> *E* is a value
- Could handle local binding using state, but have assumption that evaluating expressions doesn't alter the environment
- We will use substitution here instead
- **Notation**: *E* [*E'* / *I*] means replace all free occurrence of *I* by *E'* in *E*

Call-by-value (Eager Evaluation)

(let I = V in E, m) --> (E[V/ I],m)

$$\frac{(E,\ m) \dashrightarrow (E'',m)}{(\text{let } I = E \text{ in } E',\ m) \dashrightarrow (\text{let } I = E'' \text{ in } E')}$$

((fun I -> E) V, m) --> (E[V / I],m)

$$\frac{(E',\ m) \dashrightarrow (E'',m)}{((\text{fun } I \text{ -> } E)\ E',\ m) \dashrightarrow ((\text{fun } I \text{ -> } E)\ E'',\ m)}$$

Call-by-name (Lazy Evaluation)

- (let I = E in E', m) --> (E' [E / I],m)
- ((fun I -> E') E, m) --> (E' [E / I],m)
- Question: Does it make a difference?
- It can depending on the language

Church-Rosser Property

- Church-Rosser Property: If E-->* E_1 and E-->* E_2, if there exists a value V such that E_1 -->* V, then E_2 -->* V
- Also called **confluence** or **diamond property**
- Example: E= 2 + 3 + 4

  E_1 = 5 + 4 E_2= 2 + 7

  V =9

Does It always Hold?

- No. Languages with side-effects tend not be Church-Rosser with the combination of call-by-name and call-by-value
- Alonzo Church and Barkley Rosser proved in 1936 the λ-calculus does have it
- Benefit of Church-Rosser: can check equality of terms by evaluating them (Given evaluation strategy might not terminate, though)