

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

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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

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Dynamic semantics

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

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Dynamic Semantics

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

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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

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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

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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 :
 $\{ \text{Precondition} \} \text{ Program } \{ \text{Postcondition} \}$
- Source of idea of *loop invariant*

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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

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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
 $(E, m) \Downarrow v$

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Simple Imperative Programming Language

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

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Natural Semantics of Atomic Expressions

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

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Booleans:

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

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

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

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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

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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 $U \text{ op } V$

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Commands

Skip: $(\text{skip}, m) \Downarrow m$

Assignment: $\frac{(E, m) \Downarrow V}{(I := E, m) \Downarrow m[I \leftarrow V]}$

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

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If Then Else Command

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

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

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While Command

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

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

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Example: If Then Else Rule

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

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Example: If Then Else Rule

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

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Example: Arith Relation

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

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Example: Identifier(s)

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

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Example: Arith Relation

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

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Example: If Then Else Rule

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

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Example: Assignment

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

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Example: Arith Op

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

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Example: Numerals

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

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Example: Arith Op

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

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Example: Assignment

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

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Example: If Then Else Rule

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

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Let in Command

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

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

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Example

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

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Example

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

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Comment

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

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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

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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

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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

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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)`

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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

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