CS 345

Programming Paradigms

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Reading Assignment

- Mitchell, Chapter 2.1

What Is a Programming Language?

- Formal notation for specifying computations, independent of a specific machine
  - Example: a factorial function takes a single non-negative integer argument and computes a positive integer result
    - Mathematically, written as fact: nat → nat
- Set of imperative commands used to direct computer to do something useful
  - Print to an output device: `printf("hello world\n");`
    - What mathematical function is "computed" by printf?

Partial and Total Functions

- Value of an expression may be undefined
  - Undefined operation, e.g., division by zero
    - 3/0 has no value
    - Implementation may halt with error condition
  - Nontermination
    - f(x) = if x=0 then 1 else f(x-2)
    - This is a partial function: not defined on all arguments
    - Cannot be detected by inspecting expression (why?)
- These two cases are "mathematically" equivalent, but operationally different (why?)

Subtle: "undefined" is not the name of a function value …

Partial and Total: Definitions

- Total function f:A→B is a subset $f \subseteq A \times B$ with
  - $\forall\ x \in A$, there is some $y \in B$ with $\langle x,y \rangle \in f$ (total)
  - If $\langle x,y \rangle \in f$ and $\langle x,z \rangle \in f$ then $y=z$ (single-valued)
- Partial function f:A→B is a subset $f \subseteq A \times B$ with
  - If $\langle x,y \rangle \in f$ and $\langle x,z \rangle \in f$ then $y=z$ (single-valued)
- Programs define partial functions for two reasons
  - What are these reasons?

Computability

- Function f is computable if some program P computes it
  - For any input x, the computation P(x) halts with output f(x)
  - Partial recursive functions: partial functions (int to int) that are computable

Halting Problem

Ettore Bugatti: "I make my cars to go, not to stop"

Halting Function

- Decide whether program halts on input
  - Given program P and input x to P,

$$\underline{\text{Halt}}(P,x) = \begin{cases} \text{yes} & \text{if } P(x) \text{ halts} \\ \text{no} & \text{otherwise} \end{cases}$$

Clarifications

- Assume program P requires one string input x
- Write P(x) for output of P when run in input x
- Program P is string input to <u>Halt</u>

Fact: There is no program for <u>Halt</u>

Unsolvability of the Halting Problem

- Suppose P solves variant of halting problem
  - On input Q, assume $P(Q) = \begin{cases} \text{yes} & \text{if } Q(Q) \text{ halts} \\ \text{no} & \text{otherwise} \end{cases}$
- Build program D
  - $D(Q) = \begin{cases} \text{run forever} & \text{if } Q(Q) \text{ halts} \\ \text{halt} & \text{if } Q(Q) \text{ runs forever} \end{cases}$
- If D(D) halts, then D(D) runs forever
- If D(D) runs forever, then D(D) halts
- Contradiction! Thus P cannot exist.

Main Points About Computability

- Some functions are computable, some are not
  - Example: halting problem
- Programming language implementation
  - Can report error if program result is undefined due to an undefined basic operation (e.g., division by zero)
  - Cannot report error if program will not terminate

Computation Rules

- The factorial function type declaration does not convey how the computation is to proceed
- We also need a computation rule
  - fact (0) = 1
  - fact (n) = n * fact(n-1)
- This notation is more computationally oriented and can almost be executed by a machine

Factorial Functions

- C, C++, Java:

```
int fact (int n)  { return (n == 0) ? 1 : n * fact (n-1); }
```

- Scheme:

```
(define fact
    (lambda (n)  (if (= n 0) 1 (* n (fact (- n 1))))))
```

- ML:

```
fun fact n = if n=0 then 1 else n*fact(n-1);
```

- Haskell:
  - `fact :: Integer->Integer`
  - `fact 0 = 1`
  - `fact n = n*fact(n-1)`

Principal Paradigms

- Imperative / Procedural
- Functional / Applicative
- Object-Oriented
- Concurrent
- Logic
- Scripting

- In reality, very few languages are "pure"
  - Most combine features of different paradigms

Where Do Paradigms Come From?

- Paradigms emerge as the result of social pr s in which people develop ideas
  and create principles and practices that embody those ideas
  - Thomas Kuhn. “The Structure of Scientific Revolutions.”
- Programming paradigms are the result of people’s ideas about how programs should be constructed
  - … and formal linguistic mechanisms for expressing them
  - … and software engineering principles and practices for using the resulting programming language to solve problems

Imperative Paradigm

- Imperative (procedural) programs consists of actions to effect state change, principally through assignment operations or side effects
  - Fortran, Algol, Cobol, PL/I, Pascal, Modula-2, Ada, C
  - Why does imperative programming dominate in practice?
- OO programming is not always imperative, but most OO languages have been imperative
  - Simula, Smalltalk, C++, Modula-3, Java
  - Notable exception: CLOS (Common Lisp Object System)

Functional and Logic Paradigms

- Focuses on function evaluation; avoids updates, assignment, mutable state, side effects
- Not all functional languages are “pure”
  - In practice, rely on non-pure functions for input/output and some permit assignment-like operators
    - E.g., (set! x 1) in Scheme
- Logic programming is based on predicate logic
  - Targeted at theorem-proving languages, automated reasoning, database applications
  - Recent trend: declarative programming

Concurrent and Scripting Languages

- Concurrent programming cuts across imperative, object-oriented, and functional paradigms
- Scripting is a very "high" level of programming
  - Rapid development; glue together different programs
  - Often dynamically typed, with only int, float, string, and array as the data types; no user-defined types
  - Weakly typed: a variable 'x' can be assigned a value of any type at any time during execution
- Very popular in Web development
  - Especially scripting active Web pages

Unifying Concepts

- Unifying language concepts
  - Types (both built-in and user-defined)
    - Specify constraints on functions and data
    - Static vs. dynamic typing
  - Expressions (e.g., arithmetic, boolean, strings)
  - Functions/procedures
  - Commands
- We will study how these are defined syntactically, used semantically, and implemented pragmatically

Design Choices

- C: Efficient imperative programming with static types
- C++: Object-oriented programming with static types and ad hoc, subtype and parametric polymorphism
- Java: Imperative, object-oriented, and concurrent programming with static types and garbage collection
- Scheme: Lexically scoped, applicative-style recursive programming with dynamic types
- Standard ML: Practical functional programming with strict (eager) evaluation and polymorphic type inference
- Haskell: Pure functional programming with non-strict (lazy) evaluation.

Abstraction and Modularization

- Re-use, sharing, extension of code are critically important in software engineering
- Big idea: detect errors at compile-time, not when program is executed
- Type definitions and declarations
  - Define intent for both functions/procedures and data
- Abstract data types (ADT)
  - Access to local data only via a well-defined interface
- Lexical scope

Static vs. Dynamic Typing

- Static typing
  - Common in compiled languages, considered “safer”
  - Type of each variable determined at compile-time; constrains the set of values it can hold at run-time
- Dynamic typing
  - Common in interpreted languages
  - Types are associated with a variable at run-time; may change dynamically to conform to the type of the value currently referenced by the variable
  - Type errors not detected until a piece of code is executed

Billion-Dollar Mistake

Failed launch of Ariane 5 rocket (1996)

- $500 million payload; $7 billion spent on development

Cause: software error in inertial reference system

- Re-used Ariane 4 code, but flight path was different
- 64-bit floating point number related to horizontal velocity converted to 16-bit signed integer; the number was larger than 32,767; inertial guidance crashed

Program Correctness

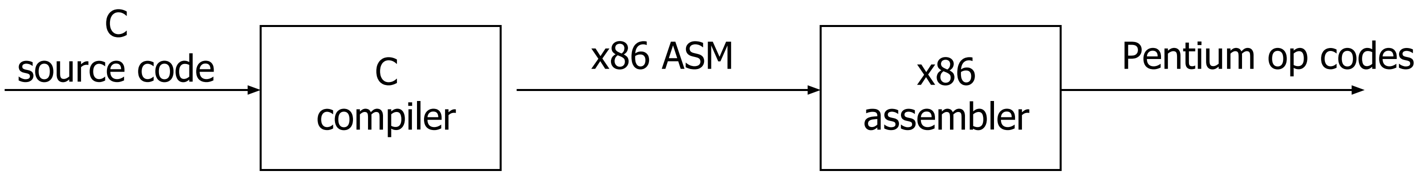
- Assert formal correctness statements about critical parts of a program and reason effectively
  - A program is intended to carry out a specific computation, but a programmer can fail to adequately address all data value ranges, input conditions, system resource constraints, memory limitations, etc.
- Language features and their interaction should be clearly specified and understandable
  - If you do not or can not clearly understand the semantics of the language, your ability to accurately predict the behavior of your program is limited

Language Translation

- Native-code compiler: produces machine code
  - Compiled languages: Fortran, C, C++, SML …
- Interpreter: translates into internal form and immediately executes (read-eval-print loop)
  - Interpreted languages: Scheme, Haskell, Python …
- Byte-code compiler: produces portable bytecode, which is executed on virtual machine (e.g., Java)
- Hybrid approaches
  - Source-to-source translation (early C++ → C→compile)
  - Just-in-time Java compilers convert bytecode into native machine code when first executed

Language Compilation

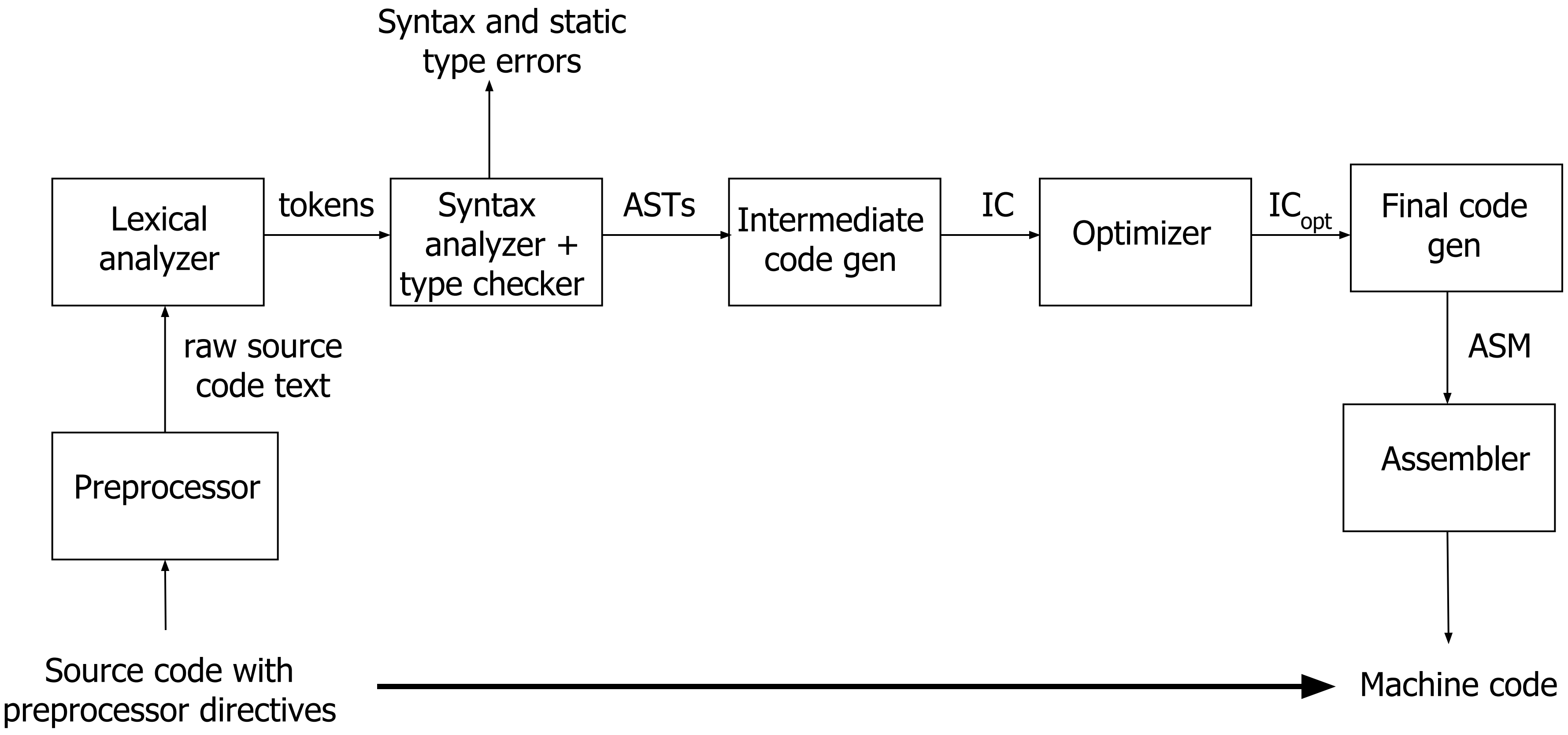
- Compiler: program that translates a source language into a target language
  - Target language is often, but not always, the assembly language for a particular machine



Checks During Compilation

- Syntactically invalid constructs
- Invalid type conversions
  - A value is used in the "wrong" context, e.g., assigning a float to an int
- Static determination of type information is also used to generate more efficient code
  - Know what kind of values will be stored in a given memory region during program execution
- Some programmer logic errors
  - Can be subtle: `if (a = b) …` instead of `if (a == b) …`

Compilation Process

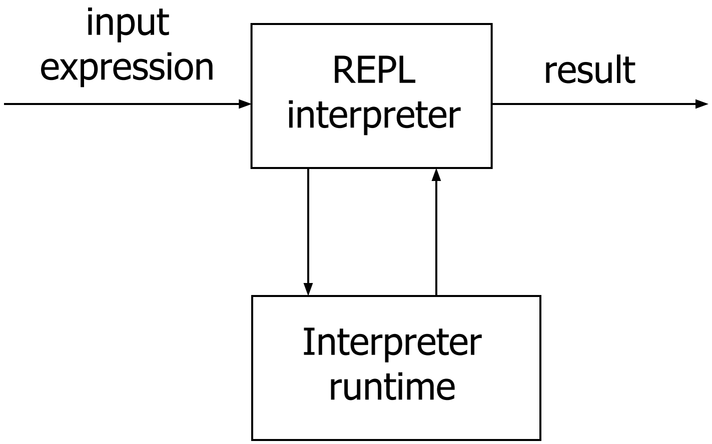


Phases of Compilation

- Preprocessing: conditional macro text substitution
- Lexical analysis: convert keywords, identifiers, constants into a sequence of tokens
- Syntactic analysis: check that token sequence is syntactically correct
  - Generate abstract syntax trees (AST), check types
- Intermediate code generation: “walk” the ASTs and generate intermediate code
  - Apply optimizations to produce efficient code
- Final code generation: produce machine code

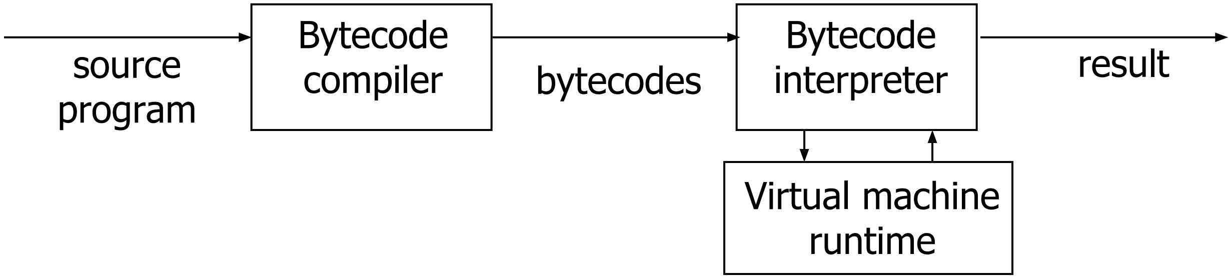
Language Interpretation

- Read-eval-print loop
  - Read in an expression, translate into internal form
  - Evaluate internal form
    - This requires an abstract machine and a "run-time" component (usually a compiled program that runs on the native machine)
  - Print the result of evaluation
  - Loop back to read the next expression



Bytecode Compilation

- Combine compilation with interpretation
  - Idea: remove inefficiencies of read-eval-print loop
- Bytecodes are conceptually similar to real machine opcodes, but they represent compiled instructions to a <u>virtual</u> machine instead of a real machine
  - Source code statically compiled into a set of bytecodes
  - Bytecode interpreter implements the virtual machine
  - In what way are bytecodes "better" then real opcodes?


source program
Bytecode compiler
bytecodes
Bytecode interpreter
result
Virtual machine runtime

Binding

- Binding = association between an object and a property of that object
  - Example: a variable and its type
  - Example: a variable and its value
- A language element is bound to a property at the time that property is defined for it
  - Early binding takes place at compile-time
  - Late binding takes place at run-time