Warm-up question

- Which of these Java programs compile, and what (if any) output do they print?

```
class Shadowing1 {
    public static int x = 9;
    public static void main (String[] args) {
        int x = 5;
        System.out.println(x);
}   }

class Shadowing2 {
    public static void main (String[] args) {
        int x = 5; int y = 8;
        if (x == 5) {
            int y = 6;
        }
        System.out.println(x+y);
}   }

class Shadowing3 {
    public static void main(String[] args) {
        if (true != false) {
            x = 6;
        }
        int x = 5;
        System.out.println(x);
}   }
```

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Mike Lam, Professor

$$y = 2x + 5$$

Variables and Scoping

Course outline

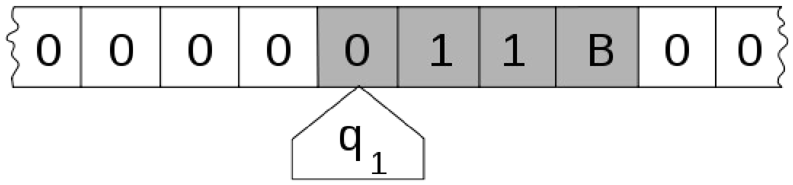
- Syntax (modules 2-3)
- **Semantics** (modules 5-8, 10-11, and 13-14)
  - Variables and scoping
  - Types and type checking
  - Expressions and control structures
  - Parameters and subprograms
- Implementation (modules 16 and 18-19)
  - Activation and environments
  - Abstraction and OOP
  - Concurrency and Error Handling
- History (module 20)

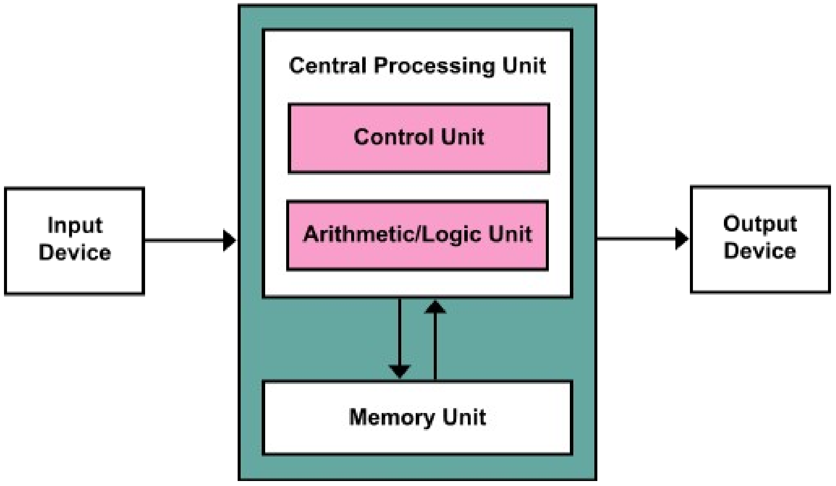
Variables

- What is a variable?

Variables

- Most languages are Turing-complete
  - Read/write head that moves left and right in memory
- Most computers use a von Neumann architecture
  - Programs read and write to cells in memory
  - Need to access individual cells (or groups of cells)
  - Actual location is less relevant





Variables

- A variable is an abstraction of memory cells
- Six main attributes/properties:
  - Name
  - Address
  - Value
  - Type
  - Lifetime
  - Scope

Binding

- Binding: attribute/property association
  - Bindings begin at binding time
    - Language design/implementation time
    - Compile time
    - Load/link time
    - Run time
  - Bindings are usually either static or dynamic
    - Static bindings begin before the program is executed and do not change during execution
    - Dynamic bindings may begin or change during execution

Name

- Name: string of characters that serves as an identifier
  - Case sensitivity
  - Special characters with meanings (e.g., $ and @ in Ruby)
  - Standards or conventions (e.g., `camelCase` vs. `under_scores`)
  - Semantic significance (e.g., type in FORTRAN and Prolog)
- Keyword vs. reserved word
  - Keyword: string of characters with special meaning
  - Reserved word: string of characters that cannot be used as a variable name (may or may not be a keyword)
- Name bindings are usually static
  - Often created by a declaration
  - Not all variables have a name!

Address

- Address: location of a variable in memory
  - Sometimes called l-value
- Address bindings may be static or dynamic
  - Creation of this binding is called allocation
- Aliases: multiple variables with identical addresses

x = a + 5

(uses x’s l-value)

Value

- Value: contents of the memory associated with a variable
  - Sometimes called r-value
- Value bindings are usually dynamic
  - Otherwise, they wouldn't be "variable"
  - First binding is called initialization
  - Important exception: named constants
  - Purely-functional languages (e.g., Haskell) are also an exception

$$x = a + 5$$

(uses a’s r-value)

Type

- Type: range of values a variable can store
  - And the operations that can be applied to it
  - Common primitive types: integer, real number, boolean, character
  - Common composite types: array/string, pointer, record, union, object
- Implicit vs. explicit binding
  - `int x = 5` vs. `x = 5`
- Static vs. dynamic typing
  - The latter allows a variable's type to change at runtime
  - Requires the system to track a type for each variable in memory
- Type inference
  - A language can be both implicitly and statically typed!

Type binding examples

- Java (explicit static)

```
int x = 5;
x = “hello”;      // compiler error
```

- JavaScript (implicit dynamic)

```
var x = 5;        // x is an int
x = “hello”;      // now it’s a String
```

- Java 10 (implicit static)

```
var x = 5;        // x is inferred to be an int
x = “hello”;      // compiler error
```

Lifetime

- Lifetime: duration of address/storage binding
  - Period of time that the variable is available
- Common lifetimes are based on location:
  - Static: entire program execution
  - Stack-dynamic: single function execution
  - Heap: arbitrary
    - Binding is created at allocation
    - Binding is destroyed at deallocation

Lifetime

- Explicit heap-dynamic: nameless memory accessed w/ pointers or references (e.g., C/C++ or Java)
  - Allocated explicitly (e.g., `malloc` in C or `new` in C++ or Java)
  - Can be deallocated explicitly (e.g., `free` in C and `delete` in C++)
    - Some languages (e.g., Rust) have delegation mechanisms
  - Can be deallocated implicitly (e.g., garbage collection in Java)
- Implicit heap-dynamic: allocated only when assigned a value (e.g., arrays in Javascript)
  - Reallocated when assigned a different value
  - Deallocated implicitly

We will consider instance variables to be explicit or implicit according to the object they belong to; this is somewhat ambiguous in our textbook

Scope

- Scope: program range where a variable is visible
  - A variable is visible if it can be referenced without qualification
    - E.g., just "`x`" instead of "`Foo::Bar::x`"
  - Many possible ranges (e.g., block, function, global, package)
  - OOP brings even more possibilities (public, private, protected)
- Local vs. non-local variables
  - A variable is local in the scope where it is declared
  - Local variables shadow (hide) non-local variables w/ same name
  - Sometimes shadowed variables are still accessible w/ qualification
- Often related to lifetime
  - But not necessarily! (e.g., `static` local in C)

Scope

- Static (lexical) vs. dynamic scoping
  - Code structure vs. call structure
  - Both involve finding a variable (name resolution) by searching through a hierarchy of scopes
    - Static scoping: compiler can do the search
    - Dynamic scoping: search the stack at runtime
  - Dynamic scoping is rare now and usually optional
    - Example: “`my`” (static) vs. “`local`” (dynamic) in Perl

Referencing Environment

- Referencing environment: all variables visible at some statement **without qualification**
  - Local scope plus ancestor scopes
  - Related concept from compilers: nested symbol tables
  - Which variables are visible at the blue and green statements?

```
class Shadowing4 {
    public static void main(String[] args) {
        System.out.println(args[0]);
        if (true != false) {
            int x = 5;
            System.out.println(x);
        }
    }
}
```

Environment at blue: { main.**args**:*string* }
Environment at green: { main.**args**:*string*, main.**x**:*int* }

Static/dynamic scoping example

- For both static and dynamic scoping:
  - What are the referencing environments at location A, B, and C?
  - What is the output?

```
program p {
  int x = 5
  int y = 2
  // LOCATION A
  func g() {
    int x = 12
    int z = 8
    // LOCATION B
    f()
  }
  func f() {
    // LOCATION C
    println(x)
  }
  g()
}
```

Static scoping:

A: { p.**x**:*int*, p.**y**:*int* }

B: { p.**y**:*int*, g.**x**:*int*, g.**z**:*int* }

C: { p.**x**:*int*, p.**y**:*int* }

Output: “5”

Dynamic scoping:

A: { p.**x**:*int*, p.**y**:*int* }

B: { p.**y**:*int*, g.**x**:*int*, g.**z**:*int* }

C: { p.**y**:*int*, g.**x**:*int*, g.**z**:*int* }

Output: “12”

Scoping nuances

- Some languages allow mixing of declarations and code (e.g., C99)
  - Scope is usually from declaration to end of program unit
- Some languages require declaration before reference
  - Declaration order can influence scoping
- Block-structured languages often restrict scope of declarations in a block
  - Sometimes allow duplicate names within a larger enclosing scope
- Many languages do not require explicit declarations (e.g., Ruby)
  - Scoping often defaults to function-level (why not block?)
- Scoping is usually enforced by compiler/interpreter, but not always
  - In Python, “private” class fields (starting w/ underscores) aren’t private!

Scoping nuances

- "Global" can mean different things
  - In Ruby, global variables are truly global (accessible from entire program)
  - In C, "global" variables are actually only accessible from code in the same module (`extern` required to access it from a different file)
  - In Python, global variables must be marked in functions that wish to use them, and must be tagged with module name outside the module

Global scoping example

- What does this Python program print?

```
x = 5

def bar():
    print(x)

def baz():
    x = 7
    print(x)

def bam():
    global x
    x = 7

bar()
baz()
print(x)
bam()
print(x)
```

```
x = 5

def hipster():
    print(x)
    x = 4
    print(x)

hipster()
```

Block scoping examples

- Ruby:

```
def foo()
    if someTest()
        x = 5
    else
        x = 7
    end
    return x
end
```

- Java:

```
/* compiler error! */
int foo() {
    if (someTest()) { int x = 5; }
    else            { int x = 7; }
    return x;
}

/* OK */
int foo() {
    int x;
    if (someTest()) { x = 5; }
    else            { x = 7; }
    return x;
}
```

Conclusion

- Variables are complicated!
  - Perhaps more so than you realized before
  - Many decisions are made at language design time
  - These decisions impact programmers a LOT
  - In general, consistency and simplicity are key
    - Principle of Least Surprise

Case studies

- Questions
  - What is the name, address, value, type, lifetime, and scope?
  - Are the bindings static or dynamic?
- Cases
  - Java “private” class instance variable
    - What would be different in C++?
  - Java "public static final" class variable
  - C local loop index variable
    - i.e., “`for (int i = 0; i < N; i++)`”

Reminder: common lifetimes include

- Static
- Stack dynamic
- Explicit heap dynamic
- Implicit heap dynamic

Case studies

```
Java "private" class instance variable
  name:     static, bound at compile time
  address:  dynamic, bound on object instantiation
  value:    dynamic, bound on every assignment
  type:     static, bound at compile time
  lifetime: explicit heap dynamic: object instantiation to garbage collection
  scope:    static, all methods in class

Java “public static final” class variable
  name:     static, bound at compile time
  address:  static, bound at compile time
  value:    static, bound at compile time
  type:     static, bound at compile time
  lifetime: static, entire execution
  scope:    static, all code that can see the class

C local loop index variable
  name:     static, bound at compile time
  address:  dynamic, bound at function entry
  value:    dynamic, re-bound on every loop iteration
  type:     static, bound at compile time
  lifetime: stack dynamic, during function execution
  scope:    static, loop body
```