

Programming Languages

Variables and Storage

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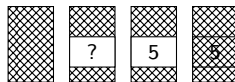
6 Summary

Storage

- Functional language variables: math like, defined or solved. Remains same afterwards.
- Imperative language variables: variable has a state and value. It can be assigned to different values in same phrase.
- Two basic operations on a variable: [inspect](#) and [update](#).

Computer memory can be considered as a collection of **cells**.

- Cells are initially **unallocated**.
- Then, **allocated/undefined**.
Ready to use but value unknown.
- Then, **storable**
- After the including block terminates, again **unallocated**



```
f();
void f() {
    int x;
    ...
    x=5;
    ...
    return;
}
```

Total or Selective Update

- Composite variables can be inspected and updated in total or selectively

```
■ struct Complex { double x,y; } a, b;  
...  
a=b; // Total update  
a.x=b.y*a.x; // Selective update
```

- Primitive variables: single cell
Composite variables: nested cells

Array Variables

Different approaches exist in implementation of array variables:

- 1 Static arrays
- 2 Dynamic arrays
- 3 Flexible arrays

Static arrays

- Array size is fixed at compile time to a constant value or expression.
- C example:

```
#define MAXELS 100  
int a[10];  
double x[MAXELS*10][20];
```

Dynamic arrays

- Array size is defined when variable is allocated. Remains constant afterwards.
- Example: C90/GCC (not in ANSI)

```
int f(int n) {  
    double a[n]; ...  
}
```

- Example: C++ with [templates](#)

```
template<class T> class Array {  
    T *content;  
public:  
    Array(int s) { content=new T[s]; }  
    ~Array()     { delete [] content; }  
};  
...  
Array<int>    a(10);  
Array<double> b(n);
```


Flexible arrays

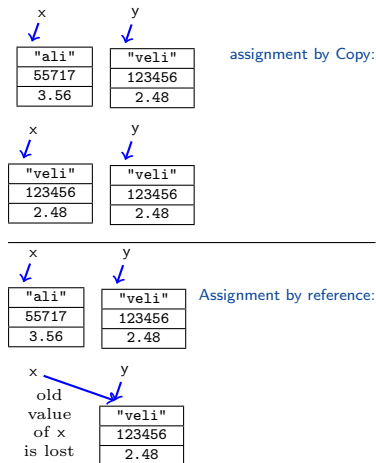
- Array size is completely variable. Arrays may expand or shrink at run time. Script languages like Perl, PHP, Python
- Perl example:

```
@a=(1,3,5);           # array size: 3
print $#a , "\n";      # output: 2 (0..2)
$a[10] = 12;           # array size 11 (intermediate elements undefined)
$a[20] = 4;            # array size 21
print $#a , "\n";      # output: 20 (0..20)
delete $a[20];         # last element erased, size is 11
print $#a , "\n";      # output: 10 (0..10)
```

- C++ and object orient languages allow overload of [] operator to make flexible arrays possible. STL (Standard Template Library) classes in C++ like `vector`, `map` are like such flexible array implementations.

Semantic of assignment in composite variables

- Assignment by **Copy** vs **Reference**.
- **Copy**: All content is copied into the other variables storage. Two copies with same values in memory.
- **Reference**: Reference of variable is copied to other variable. Two variables share the same storage and values.



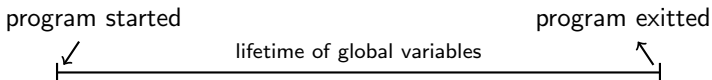
- Assignment semantics is defined by the language design
- C structures follows copy semantics. Arrays cannot be assigned. Pointers are used to implement reference semantics. C++ objects are similar.
- Java follows copy semantics for primitive types. All other types (objects) are reference semantics.
- Copy semantics is slower
- Reference semantics cause problems from storage sharing (all operations effect both variables). Deallocation of one makes the other invalid.
- Java provides copy semantic via a member function called `copy()`. Java garbage collector avoids invalid values (in case of deallocation)

Variable Lifetime

- **Variable lifetime:** The period between allocation of a variable and deallocation of a variable.
- 4 kinds of variable lifetime.
 - 1 Global lifetime (while program is running)
 - 2 Local lifetime (while declaring block is active)
 - 3 Heap lifetime (arbitrary)
 - 4 Persistent lifetime (continues after program terminates)

Global lifetime

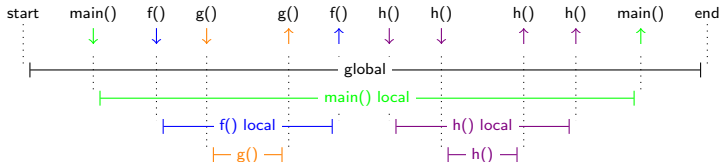
- Life of global variables start at program startup and finishes when program terminates.
- In C, all variables not defined inside of a function (including `main()`) are global variables and have global lifetime:



- What are static variables inside functions in C?

Local lifetime

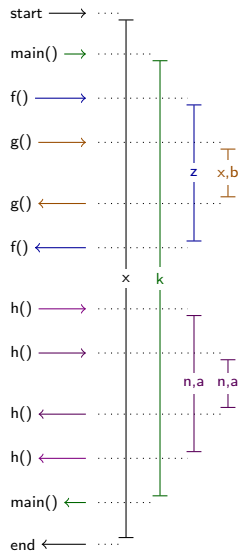
- Lifetime of a local variable, a variable defined in a function or statement block, is the time between the declaring block is activated and the block finishes.
- Formal parameters are local variables.
- Multiple instances of same local variable may be alive at the same time in recursive functions.



```

double x;
int h(int n) {
    int a;
    if (n<1) return 1
    else return h(n-1);
}
void g() {
    int x;
    int b;
    ...
}
int f() {
    double z;
    ...
    g();
    ...
}
int main() {
    double k;
    f();
    ...
    h(1);
    ...;
    return 0;
}

```



Heap Variable Lifetime

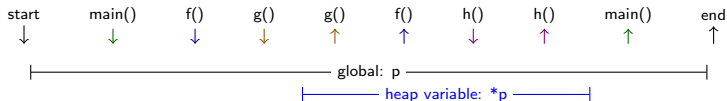
- **Heap variables:** Allocation and deallocation is not automatic but explicitly requested by programmer via function calls.
- C: `malloc()`, `free()`, C++: `new`, `delete`.
- Heap variables are accessed via pointers. Some languages use references

```
double *p;  
p=malloc(sizeof(double));  
*p=3.4; ...  
  
free(p);
```
- **p and *p are different variables** p has pointer type and usually a local or global lifetime, *p is heap variable.
- heap variable lifetime can start or end at anytime.


```

double *p;
int h() { ...
}
void g() { ...
    p=malloc(sizeof(double));
}
int f() { ...
    g(); ...
}
int main() { ...
    f();      ...
    h();      ...;
    free(p);  ...
}

```



Dangling Reference

- **dangling reference**: trying to access a variable whose lifetime is ended and already deallocated.

```

char *p, *q;

p=malloc(10);
q=p;
...
free(q);
printf("%s",p);

char *f() {
    char a[]="ali";
    ....
    return a;
}
....
char *p;
p=f();
printf("%s",p);

```

- both p's are deallocated or ended lifetime variable, thus dangling reference
- sometimes operating system tolerates dangling references. Sometimes generates run-time errors like "protection fault", "segmentation fault" are generated.

Garbage variables

- **garbage variables:** The variables with lifetime still continue but there is no way to access.

```
char *p, *q;  
...  
p=malloc(10);  
p=q;  
...  
  
void f() {  
    char *p;  
    p=malloc(10); ...  
    return  
}  
...  
f();
```

- When the pointer value is lost or lifetime of the pointer is over, heap variable is inaccessible. (*p in examples)

Garbage collection

- A solution to dangling reference and garbage problem:
PL does management of heap variable deallocation automatically. This is called **garbage collection**. (Java, Lisp, ML, Haskell, most functional languages)
- no call like `free()` or `delete` exists.
- Language runtime needs to:
 - Keep a reference counter on each reference, initially 1.
 - Increment counter on each new assignment
 - Decrement counter at the end of the reference lifetime
 - Decrement counter at the overwritten/lost references
 - Do all these operations recursively on composite values.
 - When reference count gets 0, deallocate the heap variable

- Garbage collector deallocates heap variables having a reference count 0.
- Since it may delay execution of tasks, GC is not immediately done.
- GC usually works in a separate thread, in low priority, works when CPU is idle.
- Another but too restrictive solution to garbage: Reference cannot be assigned to a longer lifetime variable. local variable references cannot be assigned to global reference/pointer.

Persistent variable lifetime

- Variables with lifetime continues after program terminates: file, database, web service object,...
- Stored in secondary storage or external process.
- Only a few experimental language has transparent persistence. Persistence achieved via IO instructions
C files: `fopen()`, `fseek()`, `fread()`, `fwrite()`
- In object oriented languages; [serialization](#): Converting object into a binary image that can be written on disk or sent over the network.
- This way objects snapshot can be taken, saved, restored and object continue from where it remains.

Memory Management

- Memory management of variables involves architecture, operating system, language runtime and the compiler.
- A typical OS divides memory in sections (segments):
 - Stack section: run time stack
 - Heap section: heap variables
 - Data section: global variables
 - Code section: executable instructions, read only.
- Global variables are fixed at compile time and they are put in data section.
- Heap variables are stored in the dynamic data structures in heap section. Heap section grows and shrinks as new variables are allocated and deallocated.
- Heap section is maintained by language runtime. For C, it is `libc`.

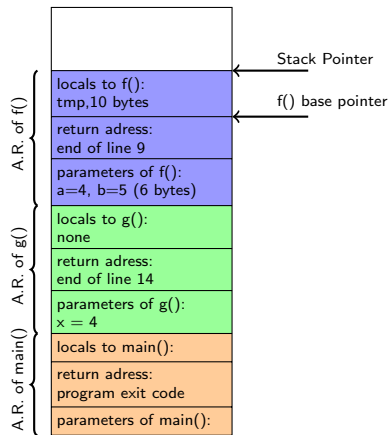
Local Variables

- Local variables can have multiple instances alive in case of recursion.
- For recursive calls of a function, there should be multiple instances of a variable and compiled code should know where it is depending on the current call state.
- The solution is to use **run-time stack**. Each function call will introduce an **activation record** to store its local context. It is also called **stack frame**, **activation frame**.
- In a typical architecture, **activation record** contains:
 - Return address. Address of the next instruction after the caller.
 - Parameter values.
 - A reserved area for local variables.


```

1  int f(short a, int b) {
2      char tmp[10];
3      ...
4      return a+b;
5  }
6  int g(int x) {
7      int tmp, p;
8      ...
9      tmp = f(x, x+1);
10     ...
11     return tmp+p;
12 }
13 int main() {
14     return g(4);
15 }

```



Function Call

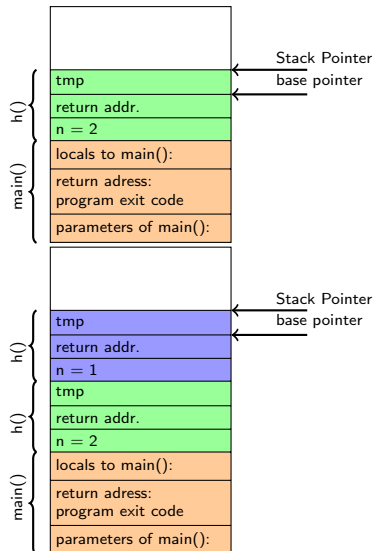
- Caller side:
 - 1 Push parameters
 - 2 Push return address and jump to function code start (usually a single CPU instruction like `callq`)
- Function entry:
 - 1 Set base pointer to current stack pointer
 - 2 Advance stack pointer to size of local variables
- Function body can access all local variables relative to base pointer
- Function return:
 - 1 Set stack pointer to base pointer
 - 2 Pop return address and jump to return address (single CPU instruction like `retq`)
- Caller side after return:
 - 1 Recover stack pointer (remove parameters on stack)
 - 2 Get and use return value if exists (typically from a register)

- All locals and parameters have the same offset from base pointer
- Recursive calls execute same instructions

```

1  int h(int n) {
2      int tmp;
3      if (n <= 1) return 0;
4      else {
5          tmp = h(n-1);
6          return n+tmp;
7      }
8  }
9  int main() {
10     printf("%d\n", h(2));
11     return 0;
12 }

```



- Order of values in the activation record may differ for different languages
- Registers are used for passing primitive value parameters instead of stack
- Garbage collecting languages keep references on stack with actual variables on heap
- Languages returning nested functions as first order values require more complicated mechanisms

```
def multiplier(a):  
    def f(x):  
        return a*x  
    return f  
  
twice = multiplier(2)  
# multiplier/a is not alive anymore but twice=f is using it  
print(twice(14))
```

Commands

Expression: program segment with a value.

Statement: program segment without a value, but alters the state.

Input, output, variable assignment, iteration...

- 1 Assignment
- 2 Procedure call
- 3 Block commands
- 4 Conditional commands
- 5 Iterative commands

Assignment

- C: “Var = Expr;”, Pascal “Var := Expr;”.
- Evaluates RHS expression and sets the value of the variable at RHS
- $x = x + 1$. LHS x is a variable reference (l-value), RHS is the value
- **multiple assignment:** $x=y=z=0$;
- **parallel assignment:** (Perl, PHP) $(\$a, \$b) = (\$b, \$a)$;
 $(\$name, \$surname, \$no) =$
 $(\text{"Onur"}, \text{"Şehitoğlu"}, 55717)$;
 Assignment: “reference aggregate” \rightarrow “value aggregate”
- **assignment with operator:** $x += 3$; $x *= 2$;

Procedure call

- **Procedure:** user defined commands. Pascal: `procedure`, C: `function` returning `void`
- `void funcname(param1 , param2 , ... , paramn)`
- Usage is similar to functions but call is in a statement position (on a separate line of program)

Block commands

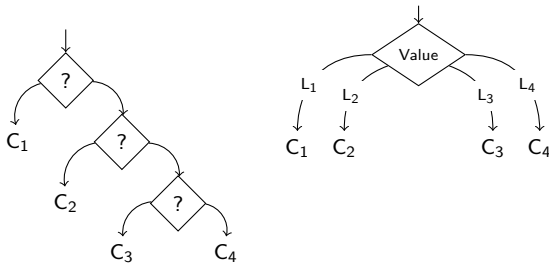
- Composition of a block from multiple statements
- **Sequential commands:** $\{ C_1 ; C_2 ; \dots ; C_n \}$
A command is executed, after it finishes the next command is executed,...
- Commands enclosed in a block behaves like single command: “if” blocks, loop bodies,...
- **Collateral commands:** $\{ C_1, C_2, \dots, C_n \}$ (not C ',')!
Commands can be executed in any order.
- The order of execution is non-deterministic. Compiler or optimizer can choose any order. If commands are independent, effectively deterministic:
'y=3 , x=x+1 ;' vs 'x=3, x=x+1 ;'
- Can be executed in parallel.

- **Concurrent commands:** concurrent paradigm languages:
 $\{ C_1 \mid C_2 \mid \dots \mid C_n \}$
- All commands start concurrently in parallel. Block finishes when the last active command finishes.
- Real parallelism in multi-core/multi-processor machines.
- Transparently handled by only a few languages. Thread libraries required in languages like Java, C, C++.

```
void producer(...) {....}  
void collectgarbage(...) {....}  
void consumer(...) {....}  
int main() {  
    ...  
    pthread_create(tid1, NULL, producer, NULL);  
    pthread_create(tid2, NULL, collectgarbage, NULL);  
    pthread_create(tid3, NULL, consumer, NULL);  
    ...  
}
```

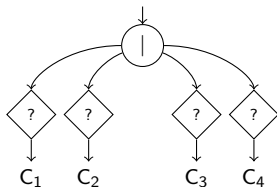
Conditional commands

- Commands to choose between alternative commands based on a condition
- in C : `if (cond) C1 else C2 ;`
`switch (value) { case L1 : C1 ; case L2 : C2 ; ... }`
- if commands can be nested for multi-conditioned selection.
- switch like commands chooses statements based on a value



- **non-deterministic conditionals:** conditions are evaluated in collaterally and commands are executed if condition holds.
- **hyphotetically:**
 if ($cond_1$) C_1 or if ($cond_2$) C_2 or if ($cond_3$) C_3 ;

 switch (val) {
 case L_1 : C_1 | case L_2 : C_2 | case L_3 : C_3 }
- Tests can run concurrently. First test evaluating to **True** wins. Others discarded.

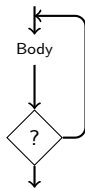
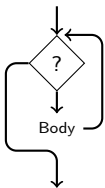


Iterative statements

- Repeating same command or command block multiple times possibly with different data or state. Loop commands.

- Loop classification: minimum number of iteration: 0 or 1.

C: while (...) { ... } C: do {...} while (...);



- Definite vs indefinite loops
- **Indefinite iteration:** Number of iterations of the loop is not known until loop finishes
- C loops are indefinite iteration loops.
- **Definite iteration:** Number of iterations is fixed when loop started.
- Pascal for loop is a definite iteration loop.
for $i := k$ to m do begin end; has $(m - k + 1)$ iterations.
Pascal forbids update of the loop index variable.
- List and set based iterations: PHP, Perl, Python, Shell

```
$colors=array('yellow','blue','green','red','white');  
foreach ($colors as $i) {  
    print $i,"_is_a_color","\n";  
}
```

Summary

- Variables with storage
- Variable update
- Lifetime: global, local, heap, persistent
- Commands