Programming Languages

Variables and Storage

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Computer Engineering

Outline

Storage

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- 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.

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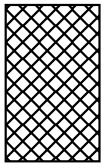

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void f() {
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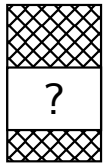


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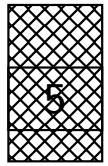
- After the including block terminates, again unallocated

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```

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:

```c
#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 u
$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.

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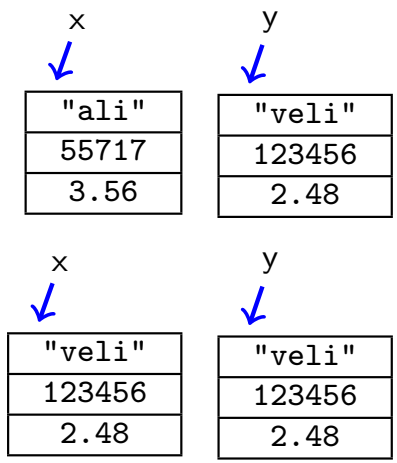
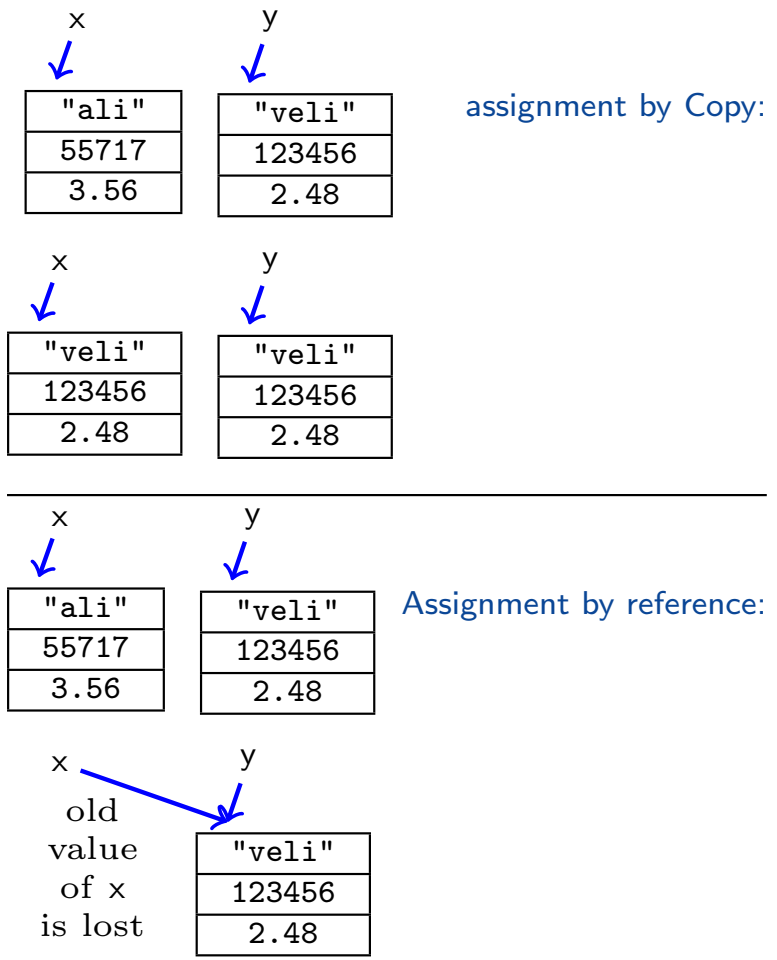


assignment by Copy:

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)

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- What are `static` variables inside functions in C?

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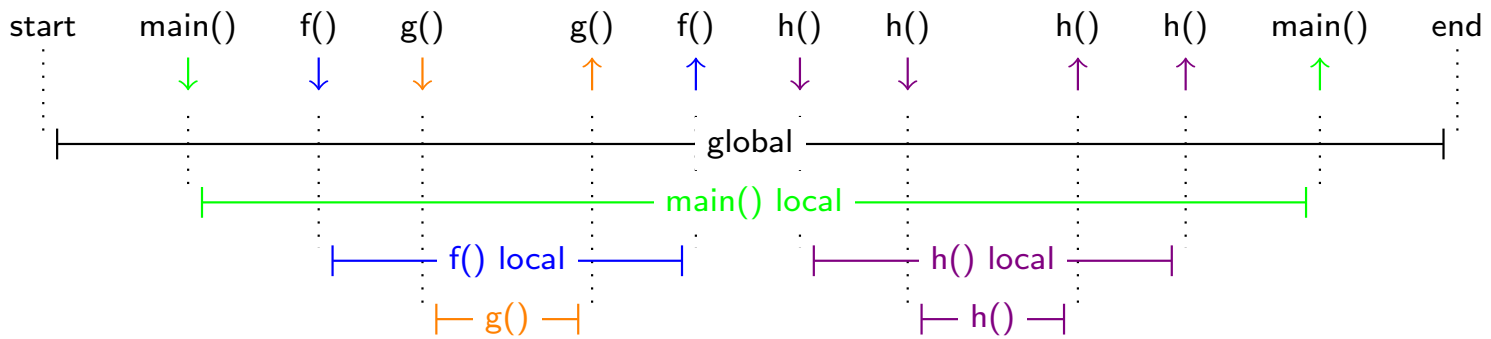
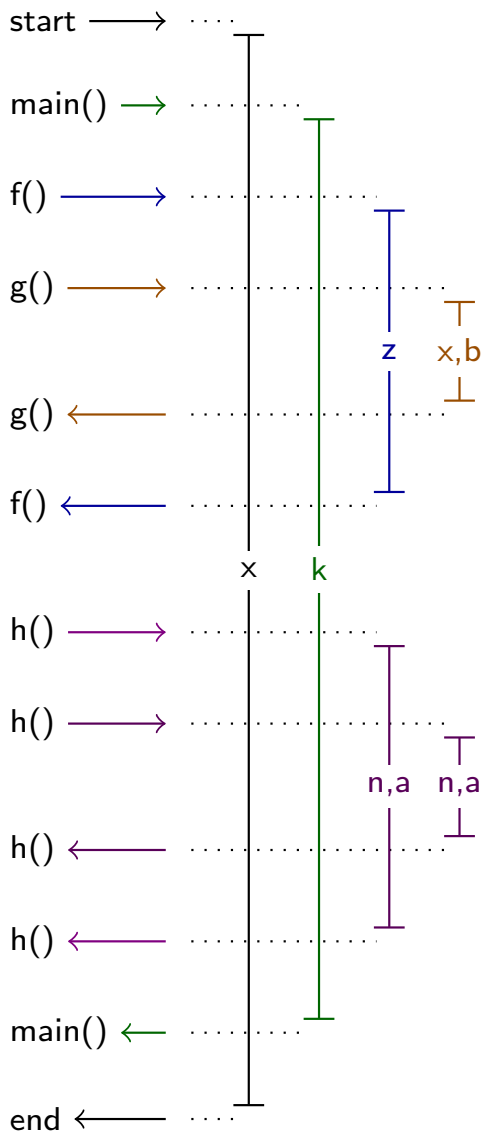


```
double x;
int h(int n) {
   int a;
   if (n<1) return 1
   else return h(n-1);
}
void g() {
   int x;
   int b;
...
}
int f() {
   double z;
   ...
   g();
   ...
}
int main() {
    double k;
    f();
    ...
    h(1);
    ...;
    return 0;
}
```



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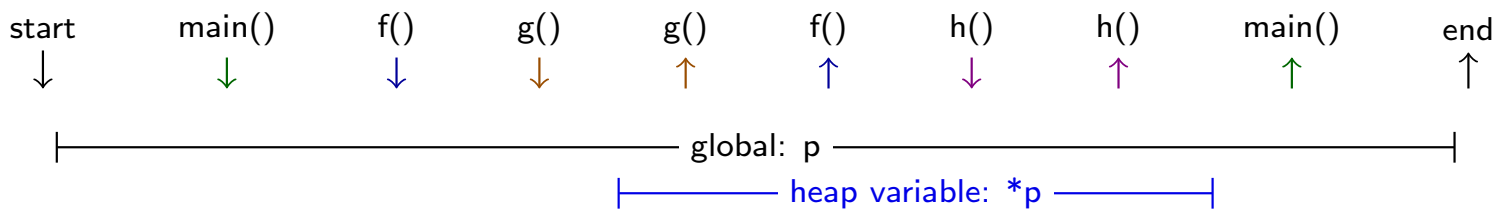
- p and *p are different variables `p` has pointer type and usually a local or global lifetime, `*p` is heap variable.
- heap variable lifetime can start or end at anytime.

```
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 erros 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 unaccessible. (*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 managemegement 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`.

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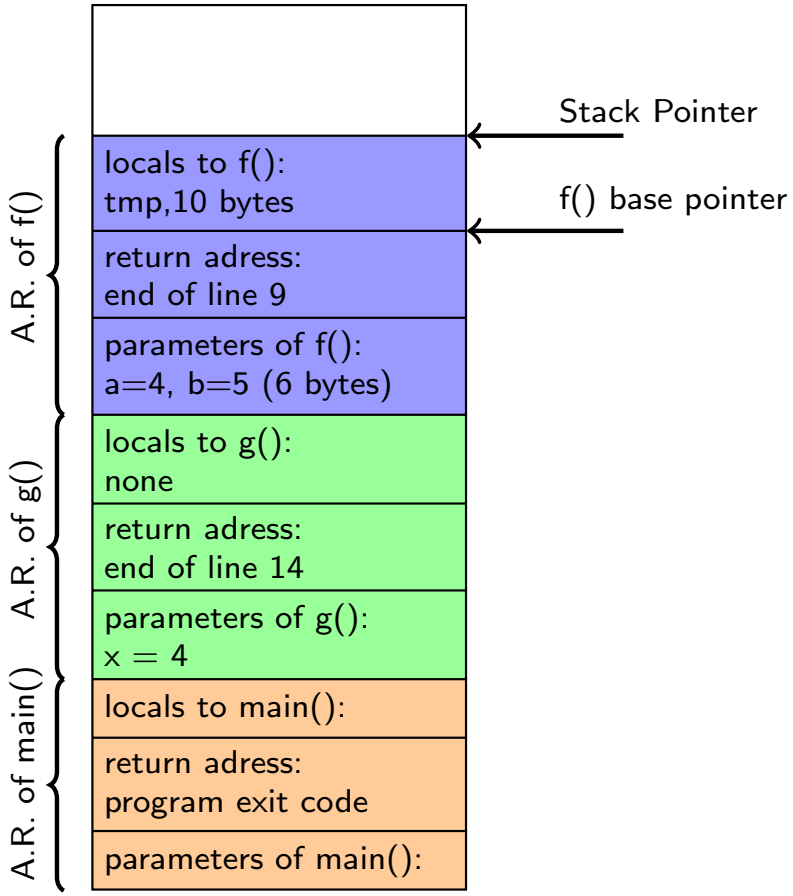
- In a typical architecture, activation record contains:
  - Return address. Address of the next instruction after the caller.
  - Parameter values.
  - A reserved area for local variables.

```
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 }
```

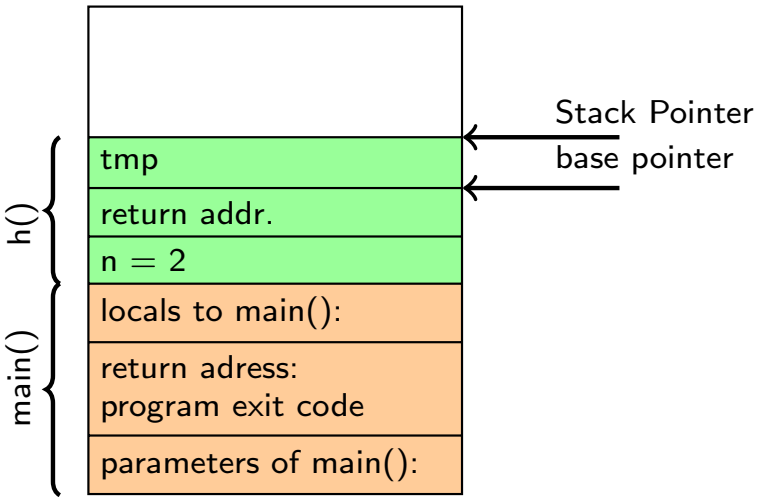


Function Call

- 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 }
```



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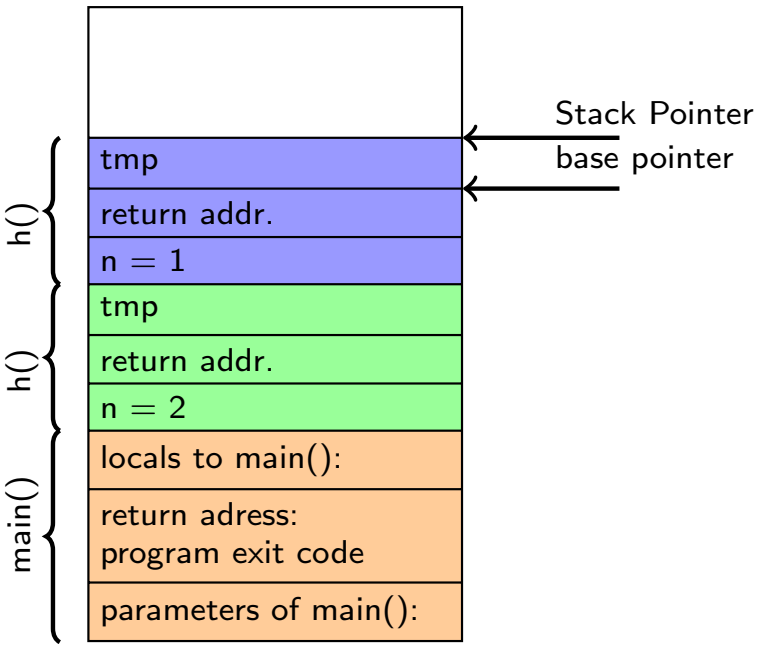


- Order of values in the activation record may differ for different languages
- Registers are used for passing primitive value parameters instead of stack
- Garbage collecting languages keep references on stack with actual variables on heap
- Languages returning nested functions as first order values 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) =
  ("Onur","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` *`functname`*`(`*`param1`*`,` *`param2`*`, ..., `*`paramn`*`)`
- Usage is similar to functions but call is in a statement position (on a separate line of program)

Block commands

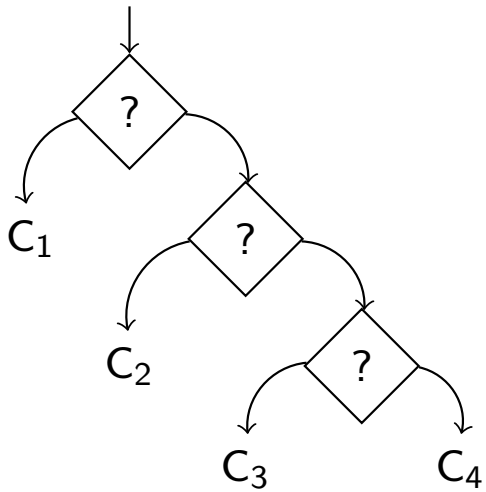
- Composition of a block from multiple statements
- Sequential commands: $\{\ C_1\ ;\ C_2;\ \ldots\ ;\ C_n\ \}$
  A command is executed, after it finishes the next command is executed,...
- Commands enclosed in a block behaves like single command: "if" blocks, loop bodies,...
- Collateral commands: $\{\ C_1,\ C_2,\ \ldots\ ,\ C_n\ \}$ (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.

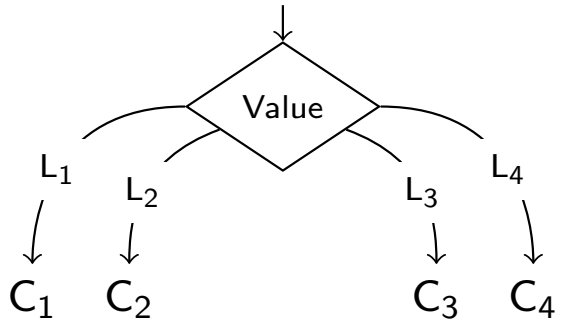
- Concurrent commands: concurrent paradigm languages:
  $\{ \; C_1 \mid C_2 \mid \ldots \mid C_n \; \}$
- All commands start concurrently in parallel. Block finishes when the last active command finishes.
- Real parallelism in multi-core/multi-processor machines.
- Transparently handled by only a few 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*`)` C_1 `else` C_2 `;`
  `switch (`*value*`) {` `case` L_1 `:` C_1 `;` `case` L_2 `:` C_2 `;` `...}`
- `if` commands can be nested for multi-conditioned selection.
- `switch` like commands chooses statements based on a value

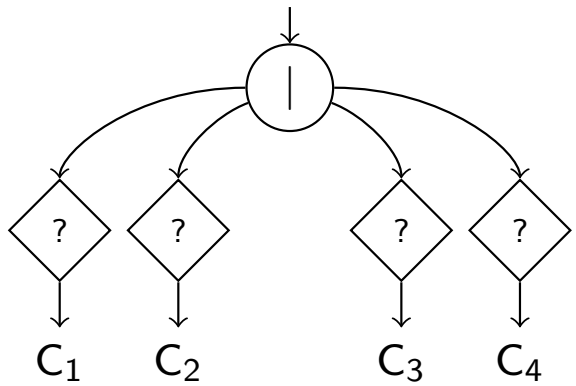




- non-deterministic conditionals: conditions are evaluated in collaterally and commands are executed if condition holds.
- hyphotetically:

  `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.



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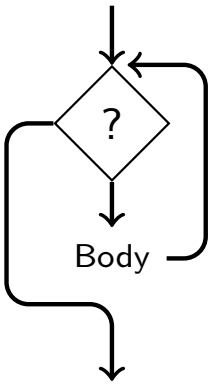
- Loop classification: minimum number of iteration: 0 or 1.

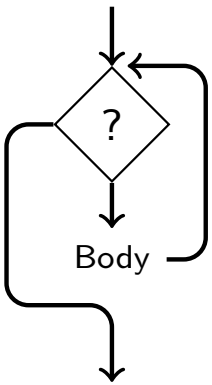
C: `while (...) { ... }`



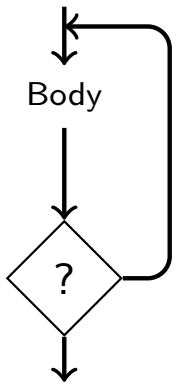
Iterative statements

- 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