CSE 504: Compilers
Evaluation and Runtime Environments

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Expression evaluation

- Order of evaluation
- For the abstract syntax tree

The equivalent expression is \((x + 3) + (2 + 4) + 5\)
One possible semantics:
- evaluate AST bottom-up, left-to-right.

This constrains optimization that uses mathematical properties of operators

(e.g. commutativity and associativity)
- e.g., it may be preferable to evaluate $e_1 + (e_2 + e_3)$ instead of $(e_1 + e_2) + e_3$
- $(x+0)+(y+3)+(z+4) = x+y+z+0+3+4 = x+y+z+7$

the compiler can evaluate $0 + 3 + 4$ at compile time, so that at runtime, we have two fewer addition operations.
Some languages leave order of evaluation unspecified. Order of evaluation of procedure parameters are also unspecified.

Problem:
- Semantics of expressions with side-effects, e.g., \((x++) + x\)
- If initial value of \(x\) is 5
  - Left-to-right evaluation yields 11 as answer, but
  - Right-to-left evaluation yields 10

So, languages with expressions with side-effects forced to specify evaluation order.

Still, a bad programming practice to use expressions where different orders of evaluation can lead to different results.

Impacts readability (and maintainability) of programs.
Left-to-right evaluation

- Left-to-right evaluation with short-circuit semantics is appropriate for boolean expressions.
  - \( e_1 \&\& e_2 \): \( e_2 \) is evaluated only if \( e_1 \) evaluates to true.
  - \( e_1 \| e_2 \): \( e_2 \) is evaluated only if \( e_1 \) evaluates to false.

- This semantics is convenient in programming:
  - Consider the statement: if((i<n) \&\& a[i]! =0)
  - With short-circuit evaluation, \( a[i] \) is never accessed if \( i \geq n \)
  - Another example: if ((p!=NULL) \&\& p->value>0)
Left-to-right evaluation (Continued)

- **Disadvantage:**
  - In an expression like “if((a==b)||(c=d))”
  - The second expression has a statement. The value of c may or may not be the value of d, depending on if a == b is true or not.

- **Bottom-up:**
  - No order specified among unrelated subexpressions.
  - Short-circuit evaluation of boolean expressions.

- **Delayed evaluation**
  - Delay evaluation of an expressions until its value is absolutely needed.
  - Generalization of short-circuit evaluation.
Control Statements

- Structured Control Statements:

- Case Statements:
  - Implementation using if-then-else
  - Understand semantics in terms of the semantics of simple constructs
  - actual implementation in a compiler

- Loops
  - while, repeat, for
If-Then-Else

- If-then-else. It is in two forms:
  - if cond then s1 else s2
  - if cond then s1

- evaluate condition: if and only if evaluates to true, then evaluate s1 otherwise evaluate s2.
Case (Switch) Statement

- Case statement
  ```
  switch(<expr>){
  case <value> :
  case <value> :
  ...
  default :
  }
  ```

- Evaluate “<expr>” to get value v. Evaluate the case that corresponds to v.

- Restriction:
  - “<value>” has to be a constant of an original type e.g., int, enum
  - Why?

```
switch (2*x) {
  case 2*y:
  case 2:
}
```
Implementation of case statement

- **Naive algorithm:**
  - Sequential comparison of value \( v \) with case labels.
  - This is simple, but inefficient. It involves \( O(N) \) comparisons.

```
switch(e){
    case 0:s0;
    case 1:s1;
    case 2:s2;
    case 3:s3;
}
```

can be translated as:

```
v = e;
if (v==0) s0;
else if (v == 1) s1;
else if (v == 2) s2;
else if (v == 3) s3;
```
Implementation of case statement (Continued)

- Binary search:
  - $O(\log N)$ comparisons, a drastic improvement over sequential search for large $N$.

- Using this, the above case statement can be translated as

```plaintext
v = e;
if (v<=1)
  if (v==0) s0;
  else if (v==1) s1;
else if (v>=2)
  if (v==2) s2;
  else if (v==3) s3;
```
Another technique is to use hash tables.

This maps the value v to the case label that corresponds to the value v.

This takes constant time (expected).

\[
\begin{cases}
\text{Target} = \text{target}[\text{hash}(v)] & \text{if } \text{hash}(v) \neq 0 \\
\text{goto } \ast \text{Target} & \text{if } \text{hash}(v) = 0
\end{cases}
\]
Control Statements (contd.)

- while:
  - let $s_1 = \text{while } C \text{ do } S$
  - then it can also be written as
    - $s_1 = \text{if } C \text{ then } \{ S; s_1 \}$

- repeat:
  - let $s_2 = \text{repeat } S \text{ until } C$
  - then it can also be written as
    - $s_2 = S; \text{ if } (!C) \text{ then } s_2$

- loop
  - let $s = \text{loop } S \text{ end}$
  - its semantics can be understood as $S; s$
  - $S$ should contain a break statement, or else it won’t terminate.
Semantics of for \((S2; C; S3)\) \(S\) can be specified in terms of while:

\[
S2; \text{while } C \text{ do } \{ S; S3 \}
\]

In some languages, additional restrictions imposed to enable more efficient code:

- Value of index variable can’t change loop body, and is undefined outside the loop
- Bounds may be evaluated only once
Unstructured control transfer statements (goto) can make programs hard to understand:

40: if (x > y) then goto 10
    if (x < y) then goto 20
    goto 30
10: x = x - y
    goto 40
20: y = y - x
    goto 40
30: gcd = x
Unstructured Control Flow (Continued)

- Unstructured control transfer statements (goto) can make programs hard to understand:

```
40: if (x > y) then goto 10
   if (x < y) then goto 20
   goto 30
10: x = x - y
   goto 40
20: y = y - x
   goto 40
30: gcd = x
```

- Equivalent program with structured control statements is easier to understand:

```
while (x!=y) {
  if (x > y) then x=x-y
  else y=y-x
}
```
goto should be used in rare circumstances
  e.g., error handling.

Java doesn’t have goto. It uses labeled break instead:

```java
l1: for (...) {
  while (...) {
      ...
      break l1.
  }
}
```

break l1 causes exit from loop labeled with l1
Restrictions in use of goto:
- jumps across procedures
- jumps from outer blocks to inner blocks or unrelated blocks

```
goto l1;
if (...) then {
  int x;  \[\text{corrected}\]
x = 5;
y = x*x;
}
```

Jumps from inner to outer blocks are permitted.
Control Statements (Continued)

- Procedure calls:
  - Communication between the calling and the called procedures takes place via parameters.

- Semantics:
  - Substitute formal parameters with actual parameters
  - Rename local variables so that they are unique in the program
    - In an actual implementation, we will simply look up the local variables in a different environment (callee’s environment)
  - Renaming captures this semantics without having to model environments.
  - Replace procedure call with the body of called procedure

```
int f(int i)
{
    int x = 2*i;
    return x;
}
```
Parameter-passing semantics

- Call-by-value
- Call-by-reference
- Call-by-value-result
- Call-by-name
- Call-by-need
- Macros

C++
If-Then-Else Parameter Passing Mechanisms

**Call-by-value**

- Evaluate the actual parameters
- Assign them to corresponding formal parameters
- Execute the body of the procedure.

```c
int p(int x) {
    x = x + 1;
    return x;
}
```

An expression `y = p(5+3)` is executed as follows:
- evaluate `5+3 = 8`, call `p` with `8`, assign `8` to `x`, increment `x`, return `x` which is assigned to `y`. 
Preprocessing
- create a block whose body is that of the procedure being called
- introduce declarations for each formal parameter, and initialize them with the values of the actual parameters

Inline procedure body
- Substitute the block in the place of procedure invocation statement.
Example:

```c
int z;
void p(int x){
    z = 2*x;
}
main(){
    int y;
    p(y);
}
```

Replacing the invocation p(y) as described yields:

```c
int z;
main(){
    int y;
    {
        int x1=y;
        z = 2*x1;
    }
}
```
“Name Capture”

- Same names may denote different entities in the called and calling procedures.
- To avoid name clashes, need to rename local variables of called procedure.
  - Otherwise, local variables in called procedure may be confused with local variables of calling procedure or global variables.
Example:

```c
int z;
void p(int x) {
    int y = 2;
    z = y * x;
}
main() {
    int y;
    p(y);
}
```

After replacement:

```c
int z;
main() {
    int y;
    {
        int x1 = y;
        int y1 = 2;
        z = y1 * x1;
    }
}
```
Call-by-reference

- Evaluate actual parameters (must have l-values)
- Assign these l-values to formal parameters
- Execute the body.
  
  ```
  int z = 8;
  y = p(z);
  ```
- After the call, y and z will both have value 9.
- Call-by-reference supported in C++, but not in C
  - Effect realized by explicitly passing l-values of parameters using “&” operator
Explicit simulation in C provides a clearer understanding of the semantics of call-by-reference:

```c
int p(int *x){
    *x = *x + 1;
    return *x;
}
...
int z;
y = p(&z);
```
Example:

```c
int z;
void p(int x){
    int y = 2;
    z = y*x;
}
main(){
    int y;
    p(y);
}
```

After replacement:

```c
int z;
main(){
    int y;
    {
        int& x1=y;
        int y1=2;
        z = y1*x1;
    }
}
```
Call-by-value-result

- Works like call by value but in addition, formal parameters are assigned to actual parameters at the end of procedure.

```c
void p (int x, int y) {
    x = x +1;
    y = y+ 1;
}
... 
int a = 3;
p(a, a) ;
```

- After the call, `a` will have the value 4, whereas with call-by-reference, `a` will have the value 5.
Call-by-value-result (Continued)

The following is the equivalent of call-by-value-result call above:

\[
\begin{align*}
x &= a; \\ y &= a; \\ x &= x + 1; \\ y &= y + 1; \\ a &= x; \\ a &= y;
\end{align*}
\]

thus, at the end, \( a = 4 \).
Example:

```c
void p(int x, y){
    x = x + 1;
    y = y + 1;
}
main(){
    int u = 3;
    p(u,u);
}
```

After replacement:

```c
main(){
    int u = 3;
    {
        int x1 = u;
        int y1 = u;
        x1 = x1 + 1;
        y1 = y1 + 1;
        u = x1; u = y1;
    }
}
```
Call-by-Name

- Instead of assigning l-values or r-values, CBN works by substituting actual parameter expressions in place of formal parameters in the body of callee.

Preprocessing:
- Substitute formal parameters in procedure body by actual parameter expressions.
- Rename as needed to avoid "name capture".

Inline:
- Substitute the invocation expression with the modified procedure body.
Call-By-Name (Continued)

● Example:

```c
void p(int x, y){
    if (x==0)
        then x=y;
    else{
        x=y+1;
    }
}
main(){
    int u=5; int v=0;
    p(v,u/v);
}
```

● After replacement:

```c
main(){
    int u=5; int v=0;
    {
        if (v==0)
            then v=u/v;
        else{
            v=u/v+1;
        }
    }
}
```
Call-By-Need

- Similar to call-by-name, but the actual parameter is evaluated at most once
  - Has same semantics as call-by-name in functional languages
    - This is because the value of expressions does not change with time
  - Has different semantics in imperative languages, as variables involved in the actual parameter expression may have different values each time the expression is evaluated in C-B-Name
Macros

- Macros work like CBN, with one important difference:
  - No renaming of “local” variables
- This means that possible name clashes between actual parameters and variables in the body of the macro will lead to unexpected results.
given

```c
#define sixtimes(y) {int z=0; z = 2*y; y = 3*z;}
main() {
    int x=5, z=3;
    sixtimes(z);
}
```

After macro substitution, we get the program:

```c
main(){
    int x=5, z=3;
    {int z=0; z = 2*z; z = 3*z;}
}
```
Macros (Continued)

- It is different from what we would have got with CBN parameter passing.

- In particular, the name confusion between the local variable z and the actual parameter z would have been avoided, leading to the following result:

```c
main() {
    int x = 5, z = 3;
    {
        int z1=0;  // z renamed as z1
        z1 = 2*z;  // y replaced by z without confusion with original z
        z = 3*z1;  // confusion with original z
    }
}
```
Difficulties in Using Parameter Passing Mechanisms

- **CBV**: Easiest to understand, no difficulties or unexpected results.

- **CBVR**:
  - When the same parameter is passed in twice, the end result can differ depending on the order in which formals are assigned back to the actual parameters.
  - Otherwise, relatively easy to understand.
Difficulties With CBVR (Continued)

Example:

```c
int f(int x, int y) {
    x=4;
    y=5;
}
void g() {
    int z;
    f(z, z);
}
```

- If assignment of formal parameter values to actual parameters were performed left to right, then z would have a value of 5.
- If they were performed right to left, then z will be 4.
If-Then-Else Parameter Passing Mechanisms

Difficulties in Using CBR

- Aliasing can create problems.
  ```c
  int rev(int a[], int b[], int size) {
    for (int i = 0; i < size; i++)
      a[i] = b[size-i-1];
  }
  ```
  The above procedure will normally copy b into a, while reversing the order of elements in b.

- However, if a and b are the same, as in an invocation rev(c,c,4), the result is quite different.

- If c is 1,2,3,4 at the point of call, then its value on exit from rev will be 4,3,3,4.
CBN is complicated, and can be confusing in the presence of side-effects.

- actual parameter expression with side-effects:

```c
void f(int x) {
    int y = x;
    int z = x;
}
main() {
    int y = 0;
    f(y++);
}
```

Note that after a call to `f`, `y`'s value will be 2 rather than 1.
If the same variable is used in multiple parameters.

```c
void swap(int x, int y) {
    int tp = x;
    x = y;
    y = tp;
}
```

```c
main() {
    int a[] = {1, 1, 0};
    int i = 2;
    swap(i, a[i]);
}
```

When using CBN, by replacing the call to swap by the body of swap: i will be 0, and a will be 2, 1, 0.
Difficulties in Using Macro

- Macros share all of the problems associated with CBN.
- In addition, macro substitution does not perform renaming of local variables, leading to additional problems.
Components of Runtime Environment (RTE)

**Static area:** allocated at load/startup time.
- Examples: global/static variables and load-time constants.

**Stack area:** for execution-time data that obeys a last-in first-out lifetime rule.
- Examples: nested declarations and temporaries.

**Heap:** a dynamically allocated area for “fully dynamic” data, i.e. data that does not obey a LIFO rule.
- Examples: objects in Java, lists in OCaml.
Languages and Environments

- Languages differ on where activation records must go in the environment:
  - (Old) Fortran is static: all data, including activation records, are statically allocated.
    - Each function has only one activation record — no recursion!
  - Functional languages (Scheme, ML) and some OO languages (Smalltalk) are heap-oriented:
    - almost all data, including AR, allocated dynamically.
  - Most languages are in between: data can go anywhere
    - ARs go on the stack.
### Procedures and the environment

- An Activation Record (AR) is created for each invocation of a procedure.

#### Structure of AR:

<table>
<thead>
<tr>
<th>Base Pointer</th>
<th>Actual parameters</th>
<th>Return value</th>
<th>Return address</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saved BP (control link)</td>
<td>Local variables</td>
<td>Temporary variables</td>
</tr>
</tbody>
</table>

- **Direction of stack growth**

![Stack diagram](image)
Procedures and the environment

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Direction of stack growth:

- `push X` 
- `decr SP`
- `move X to *SP`
- `push BP`
Local variables are allocated at a fixed offset on the stack

- Accessed using this constant offset from BP
  - Example: to load a local variable at offset 8 into the EBX register (x86 architecture)
    \[ \text{mov } 0x8(\%ebp),\%ebx \]

Example:

```c
{ int x; int y;  
  { int z; }  
  { int w; }  
}
```

<table>
<thead>
<tr>
<th>Variable</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>-8</td>
</tr>
<tr>
<td>y</td>
<td>-12</td>
</tr>
<tr>
<td>z</td>
<td>-16</td>
</tr>
<tr>
<td>w</td>
<td>-16</td>
</tr>
</tbody>
</table>

AR ↔ Stack Frame
Steps involved in a procedure call

**Caller**
- Save registers
- Evaluate actual parameters, push on the stack
  - Push l-values for CBR, r-values in the case of CBV
- Allocate space for return value on stack (unless return is through a register)
- Call: Save return address, jump to the beginning of called function

**Callee**
- Save BP (control link field in AR)
- Move SP to BP
- Allocate storage for locals and temporaries (Decrement SP)
- Local variables accessed as [BP-k], parameters using [BP+l]
Steps in return

- **Callee**
  - Copy return value into its location on AR
  - Increment SP to deallocate locals/temporaries
  - Restore BP from Control link
  - Jump to return address on stack

- **Caller**
  - Copy return values and parameters
  - Pop parameters from stack
  - Restore saved registers
Example (C):

```c
int x;
void p(int y){
    int i = x;
    char c; ...
}
void q (int a){
    int x;
    p(1);
}
main(){
    q(2);
    return 0;
}
```
Non-local variable access

- Requires that the environment be able to identify frames representing enclosing scopes.

- Using the control link results in dynamic scope (and also kills the fixed-offset property).

- If procedures can’t be nested (C), the enclosing scope is always locatable:
  - it is global/static (accessed directly)

- If procedures can be nested (Ada, Pascal), to maintain lexical scope a new link must be added to each frame:
  - access link, pointing to the activation of the defining environment of each procedure.
Access Link vs Control Link

- **Control Link** is a reference to the AR of the caller
- **Access link** is a reference to the AR of the surrounding scope
Access Link vs Control Link

- Control Link is a reference to the AR of the caller
- Access link is a reference to the AR of the surrounding scope

**Dynamic Scoping:** When an identifier is not found in the current AR, use *control link* to access caller’s AR and look up the name there
- If not found, keep walking up the control links until name is found.
Access Link vs Control Link

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**Static Scoping:** When an identifier is not found in the AR of the current function, use *access link* to get to AR for the surrounding scope and look up the name there
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Access Link vs Control Link

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  - If not found, keep walking up the access links until the name is found.

**Note:** Except for top-level functions, access links correspond to function scopes, so they cannot be determined statically
  - They need to be “passed in” like a parameter.
Access Link Vs Control Link: Example

- If p used its caller’s BP to access x, then it ends up accessing the variable x defined within p
  - This would be dynamic scoping.
  - To get static scoping, access should use q’s BP

- **Access link**: q explicitly passes a link to its BP
  - Calls to self: pass access link without change.
  - Calls to immediately nested functions: pass your BP
  - Calls to outer functions: Follow your access link to find the right access link to pass
  - Other calls: these will be invalid (like goto to an inner block)
Supporting Closures

- **Closures** are needed for
  - Call-by-name and lazy evaluation
  - Returning dynamically constructed functions containing references to variables in surrounding scope

- Variables inside closures may be accessed long after the functions defining them have returned
  - Need to “copy” variable values into the closure, or
  - Not free the AR of functions when they return,
    - i.e., allocate ARs on heap and garbage collect them
std::function<void(int a, float b)>
{
    return [a, b]() { return a + b; }
}

void f() {
    auto f = q(2, 3);
    return f();
}

x = y + z;
add y, z, x;
AST classes
- constructor
- print
- type check → mem_alloc()
- codegen
- eval
Exception Handling

Example:

```cpp
int fac(int n) {
    if (n <= 0) throw (-1); else if (n > 15) throw ("n too large");
    else return n*fac(n-1); }
void g(int n) {
    int k;
    try { k = fac(n); }
    catch (int i) { cout << "negative value invalid" ;}
    catch (char *s) { cout << s; }
    catch (...) { cout << "unknown exception" ;}
}
g(-1) will print “negative value invalid”, g(16) will print “n too large”
```
Exception Vs Return Codes

- Exceptions are often used to communicate error values from a callee to its caller. Return values provide alternate means of communicating errors.

- Example use of exception handler:

```c
float g (int a, int b, int c) {
    float x = fac(a) + fac(b) + fac(c) ; return x ; }
main() {
    try { g(-1, 3, 25); }
    catch (char *s) { cout << "Exception ‘" << s << ",'raised, exiting\n"; }
    catch (...) { cout << "Unknown exception, exiting\n"; }
}
```

- We do not need to concern ourselves with every point in the program where an error may arise.
float g(int a, int b, int c) {
    int x1 = fac(a);
    if (x1 > 0) {
        int x2 = fac(b);
        if (x2 > 0) {
            int x3 = fac(c);
            if (x3 > 0)
                return x1 + x2 + x3;
            else return x3;
        }
        else return x2;
    }
    else return x1;
}

main() {
    int x = g(-1, 2, 25);
    if (x < 0) { /* identify where error occurred, print */ }
}
Use of Exceptions in C++ Vs Java

- In C++, exception handling was an after-thought.
  - Earlier versions of C++ did not support exception handling.
  - Exception handling not used in standard libraries
  - Net result: continued use of return codes for error-checking

- In Java, exceptions were included from the beginning.
  - All standard libraries communicate errors via exceptions.
  - Net result: all Java programs use exception handling model for error-checking, as opposed to using return codes.
Implementation of Exception Handling

- Exception handling can be implemented by adding “markers” to ARs to indicate the points in program where exception handlers are available.

- In C++, entering a try-block at runtime would cause such a marker to be put on the stack.

- When exception arises, the RTE gets control and searches down from stack top for a marker.

- Exception then "handed" to the catch statement of this try-block that matches the exception.

- If no matching catch statement is present, search for a marker is continued further down the stack, and the whole process is repeated.
Memory Allocation

- A variable is stored in memory at a location corresponding to the variable.
- Constants do not need to be stored in memory.
- Environment stores the binding between variable names and the corresponding locations in memory.
- The process of setting up this binding is known as storage allocation.
Static Allocation

- Allocation performed at compile time.
- Compiler translates all names to corresponding location in the code generated by it.
- Examples:
  - all variables in original FORTRAN
  - all global and static variables in C/C++/Java
Stack Allocation

- Needed in any language that supports the notion of local variables for procedures.
- Also called “automatic allocation”, but this is somewhat of a misnomer now.
- Examples: all local variables in C/C++/Java procedures and blocks.
- Implementation:
  - Compiler translates all names to relative offsets from a location called the “base pointer” or “frame pointer”.
  - The value of this pointer varies will, in general, be different for different procedure invocations.
The pointer refers to the base of the “activation record” (AR) for an invocation of a procedure.

The AR holds such information as parameter values, local variables, return address, etc.

```c
int fact(int n){
    if n=0 then 1
    else{
        int rv = n*fact(n-1);
        return rv;
    }
}
main(){
    fact(5);
}
```
An activation record is created on the stack for each a call to function.

The start of activation record is pointed to by a register called BP.

On the first call to fact, BP is decremented to point to new activation record, n is initialized to 5, rv is pushed but not initialized.

New activation record is created for the next recursive call and so on.

When n becomes 0, stack is unrolled where successive rv’s are assigned the value of n at that stage and the rv of previous stage.
Heap Management

- Issues
  - No LIFO property, so management is difficult
  - Fragmentation
  - Locality

- Models
  - explicit allocation, free
    - e.g., malloc/free in C, new/delete in C++
  - explicit allocation, automatic free
    - e.g., Java
  - automatic allocation, automatic free
    - e.g., Lisp, OCAML, Python, JavaScript
Internal fragmentation: When asked for $x$ bytes, allocator returns $y > x$ bytes

- $y - x$ represents internal fragmentation

External fragmentation: When (small) free blocks of memory occur in between (i.e., external to) allocated blocks

- The memory manager may have a total of $M \gg N$ bytes of free memory available, but no contiguous block larger enough to satisfy a request of size $N$. 
Approaches for Reducing Fragmentation

- Use blocks of single size (early LISP)
  - Limits data-structures to use less efficient implementations.

- Use bins of fixed sizes, e.g., $2^n$ for $n = 0, 1, 2, ...$
  - When you run out of blocks of a certain size, break up a block of next available size
  - Eliminates external fragmentation, but increases internal fragmentation

- Maintain bins as LIFO lists to increase locality

- malloc implementations (Doug Lea)
  - For small blocks, use bins of size $8k$ bytes, $0 < k < 64$
  - For larger blocks, use bins of sizes $2^n$ for $n > 9$
What if a program allocates many 8 byte chunks, frees them all and then requests lots of 16 byte chunks?

- Need to coalesce 8-byte chunks into 16-byte chunks
- Requires additional information to be maintained
  - for allocated blocks: where does the current block end, and whether the next block is free
Explicit Vs Automatic Management

- Explicit memory management can be more efficient, but takes a lot of programmer effort.
- Programmers often ignore memory management early in coding, and try to add it later on.
  - But this is very hard, if not impossible.

**Result:**
- Majority of bugs in production code is due to memory management errors:
  - Memory leaks
  - Null pointer or unitialized pointer access
  - Access through dangling pointers
Managing Manual Deallocation

- How to avoid errors due to manual deallocation of memory
  - Never free memory!!!
  - Use a convention of object ownership (owner responsible for freeing objects)
    - Tends to reduce errors, but still requires a careful design from the beginning. (Cannot ignore memory deallocation concerns initially and add it later.)
  - Smart data structures, e.g., reference counting objects
  - Region-based allocation
    - When a collection of objects having equal life time are allocated
    - Example: Apache web server’s handling of memory allocations while serving a HTTP request
Garbage Collection

- Garbage collection aims to avoid problems associated with manual deallocation
  - Identify and collect garbage automatically

- What is garbage?
  - Unreachable memory

- Automatic garbage collection techniques have been developed over a long time
  - Since the days of LISP (1960s)
Garbage Collection Techniques

- Reference Counting
  - Works if there are no cyclic structures
- Mark-and-sweep
- Generational collectors

Issues
- Overhead (memory and space)
- Pause-time
- Locality
Reference Counting

- Each heap block maintains a count of the number of pointers referencing it.
- Each pointer assignment increments/decrements this count.
- Deallocation of a pointer variable decrements this count.
- When reference count becomes zero, the block can be freed.
Disadvantages:
- Does not work with cyclic structures
- May impact locality
- Increases cost of each pointer update operation

Advantages:
- Overhead is predictable, fixed
- Garbage is collected immediately, so more efficient use of space
Mark-and-Sweep

- Mark every allocated heap block as “unreachable”
- Start from registers, local and global variables
- Do a depth-first search, following the pointers
  - Mark each heap block visited as “reachable”
- At the end of the sweep phase, reclaim all heap blocks still marked as unreachable
Garbage Collection Issues

- Memory fragmentation
  - Memory pages may become sparsely populated
  - Performance will be hit due to excessive virtual memory usage and page faults
  - Can be a problem with explicit memory management as well
    - But if a programmer is willing to put in the effort, the problem can be managed by freeing memory as soon as possible

Solution:
- Compacting GC
  - Copy live structures so that they are contiguous
- Copying GC
Copying Garbage Collection

- Instead of doing a sweep, simply copy over all reachable heap blocks into a new area.
- After the copying phase, all original blocks can be freed.
- Now, memory is compacted, so paging performance will be much better.
- Needs up to twice the memory of compacting collector, but can be much faster.
  - Reachable memory is often a small fraction of total memory.
Generational Garbage Collection

- Take advantage of the fact that most objects are short-lived
- Exploit this fact to perform GC faster

Idea:
- Divide heap into generations
- If all references go from younger to older generation (as most do), can collect youngest generation without scanning regions occupied by other generations
- Need to track references from older to younger generation to make this work in all cases
Garbage collection in Java

- Generational GC for young objects
- “Tenured” objects stored in a second region
  - Use mark-and-sweep with compacting
- Makes use of multiple processors if available

References


GC for C/C++: Conservative Garbage Collection

- Cannot distinguish between pointers and nonpointers
  - Need “conservative garbage collection”

- The idea: if something “looks” like a pointer, assume that it may be one!
  - Problem: works for finding reachable objects, but cannot modify a value without being sure
    - Copying and compaction are ruled out!

- Reasonable GC implementations are available, but they do have some drawbacks
  - Unpredictable performance
  - Can break some programs that modify pointer values before storing them in memory