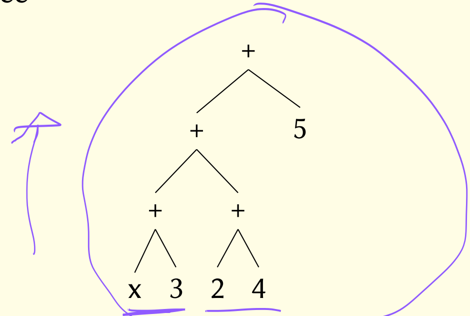
CSE 504: Compilers

Evaluation and Runtime Environments

R. Sekar

Expression evaluation

- Order of evaluation
- For the abstract syntax tree



- the equivalent expression is (x + 3) + (2 + 4) + 5

Expression evaluation (Continued)

- 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 of e1+(e2+e3)instead of (e1+e2)+e3
  - (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.

Expression evaluation (Continued)

- 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

5 6

5 5

10

5

y = (x++) + x;

y = x++;

y = y + x;

- 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.

  e1&&e2: e2 is evaluated only if e1 evaluates to true.

  e1||e2: e2 is evaluated only if e1 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>= 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 :
}
```

```
switch (2x) {
  → case 2*y:
  → case z :
}
```

- 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
    primitive
    ↳ over a "small" range
  - Why?

Implementation of case statement

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

'a'

'z'

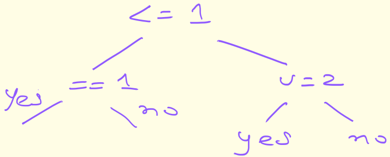
```
switch(e){
  case 0:s0;
  case 1:s1;
  case 2:s2;
  case 3:s3;
}
```

- 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;
```

N/2

Implementation of case statement (Continued)

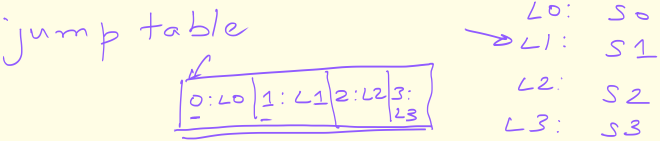


- Binary search:
  - O(log N) comparisons, a drastic improvement
  - over sequential search for large N.
- Using this, the above case statement can be translated as

```
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;
```

15000
5
1M

Implementation of case statement (Continued)



- 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).

O(1)

```
Target = target[hash(v)]
goto *Target
```

```
Target = target[v];
```

Control Statements (contd.)

- while:
  - let s1 = while C do S
  - then it can also be written as
  - s1 = if C then {S; s1}

Recursive defn of semantics

```
while ( 1 ){
}
```

- repeat:
  - let s2 = repeat S until C
  - then it can also be written as
  - s2 = S; if (!C) then s2
- loop
  - let s = loop S end
  - its semantics can be understood as S; s
  - S should contain a break statement, or else it won't terminate.

For-loop

for-each

∅

- Semantics of for (S2; C; S3) S can be specified in terms of while:
  - S2; while C 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

```
list x;
     auto
for ( i : x ) {
}
```

```
for ( i = x.begin(); i != x.end();
    ; i++){
        *i
}
```

```
for (int i ; i<n; i++){
    break;
}
i
```

Unstructured Control Flow

- 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
}
```

Control Statements (contd.)

- goto should be used in rare circumstances
  - e.g., error handling.
- Java doesn't have goto. It uses labeled break instead:

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

- break l1 causes exit from loop labeled with l1

Control Statements (contd.)

- Restrictions in use of goto:
  - jumps across procedures ✗
  - jumps from outer blocks to inner blocks or unrelated blocks ✗

```
goto l1;
if (...)  then {
  int x; = 5;
  ~~x = 5;~~
  l1:  y = x*x;
}
```

- Jumps from inner to outer blocks are permitted. ✓

Control Statements (Continued)

- Procedure calls:

  caller callee

  - 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

actual

```
int f(int i){
formal
x = 2*i;
}
```

```
f(7*5);
```

Parameter-passing semantics

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

Call-by-value

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

```
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.

Call-by-value (Continued)

- 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.

Call-by-value (Continued)

- Example:

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

- Replacing the invocation p(y) as described yields:

```
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

Call-by-value (Continued)

1. rename variable

2. assign formals from actuals

3. inline body

- Example:

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

or

```
x = y
int y = 2;
z = y * x
```

- After replacement:

```
int z;
main(){
    int y;
    {
        int x1=y;
        int y1=2;
        z = y1*x1;
    }
}
```

1 2 3 1

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

Call-by-reference (Continued)

- Explicit simulation in C provides a clearer understanding of the semantics of call-by-reference:

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

g(List z) {
⋮
}

g(y)

int x;
int y;
x = 5;
y = 3;
x = y;
x = 2;
→ y is still 3

List x = new ....
List y = new ...

x = y;
x.f(...)
→ y also changes

Call-By-Reference (Continued)

- Example:

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

x = 3;

- After replacement:

```
int z;
main(){
   int y;
   {
      int& x1=y;
      int y1=2;
      z = y1*x1;
   }
}
```

1

2

1

assignment of l-values (or locations)

x1 = 3

? y = 3

Call-by-value-result

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

```
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:

```
x = a; y =a ;
x = x +1 ;
y =y +1 ;
a =x ; a =y ;
```

- thus, at the end, a = 4.

Call-By-Value-Result (Continued)

- Example:

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

- After replacement:

```
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:

```
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:

```
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.

Macros (Continued)

Constexpr

C++17

- given

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

w = 3

- After macro substitution, we get the program:

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

z = 2*w; w = 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:

```
main() {
    int x = 5, z = 3;
    {
        int z1=0;  // z renamed as z1
        z1 = 2*z;  // y replaced by z without
        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:

```
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.

Difficulties in Using CBR

- Aliasing can create problems.

```
int rev(int a[], int b[], int size) {
   for (int i = 0; i < size; i++)
      a[i] = b[size-i-1];
}
```

int c = {1, 2, 3, 4};
4 3 3 4
rev(c,c);
c[0] = c[3]; c[1] = c[2]
c[2] = c[1] ; c[3] = c[0]

- 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.

Difficulties in Using CBN

- CBN is complicated, and can be confusing in the presence of side-effects.
  - actual parameter expression with side-effects:

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

y = 2

int y = x;
int z = y;

y = 1

- Note that after a call to f, y's value will be 2 rather than 1.

Difficulties in Using CBN (Continued)

- If the same variable is used in multiple parameters.

curried functions

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

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

int tp = i;

i = a[i];

a[i] = tp;

tp ← 2

i ← 0

a[0] ← 2

{2, 1, 0}

- 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.

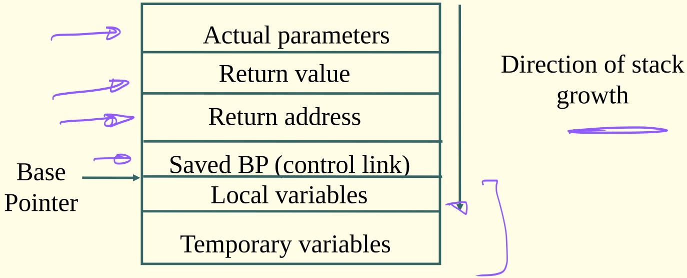
- Examples: objects in Java, lists in OCaml.

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:



Actual parameters

Return value

Return address

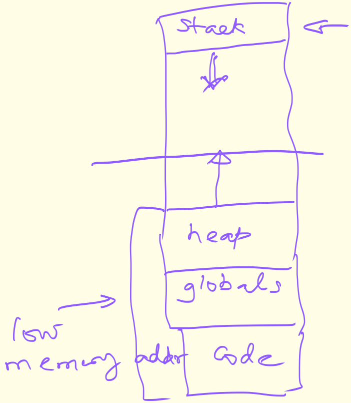
Saved BP (control link)

Local variables

Temporary variables

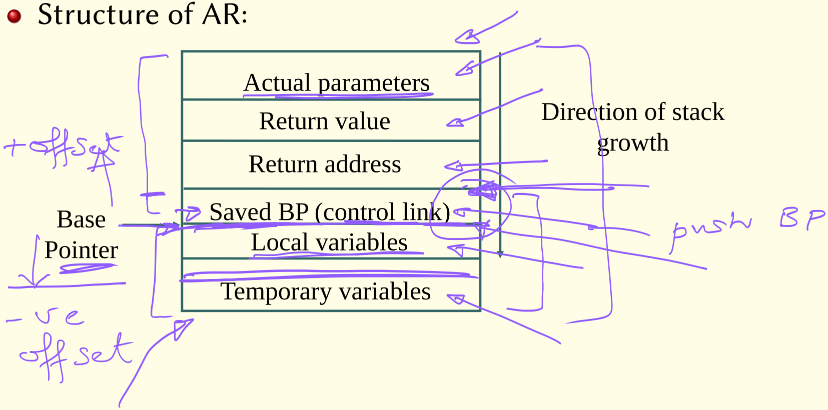
Base Pointer

Direction of stack growth



Procedures and the environment

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



push X → decr SP

move X to *SP

Access to Local Variables

- 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)

```
mov 0x8(%ebp),%ebx
```

parameter

- Example:

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

x : -8

y : -12

z : -16

w : -16

AR ⟷ Stack Frame

Steps involved in a procedure call

Application Binary Interface

ABI

- Caller
  - Save registers

    Caller save regs
  - 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]

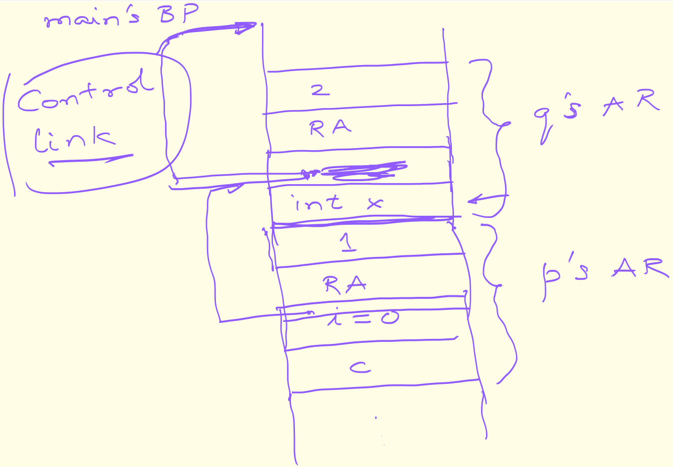
    Callee-save regs

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):

```
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).

& c++

- 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

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

Access Link vs Control Link

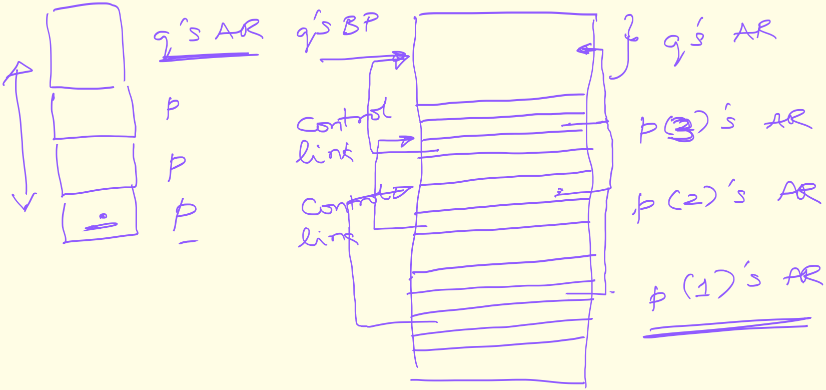
- Control Link is a reference to the AR of the caller
- Access link is a reference to the AR of the surrounding scope
- **Dynamic Scoping:** When an identifier is not found in the current AR, use *control link* to access caller's AR and look up the name there
  - If not found, keep walking up the control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

```
int q(int x) {
  int p(int y) {
    if (y==0)
      return x+y;
    else {
      int x = 2*p(y-1);
      return x;
    }
  }

  return p(3);
}
```

- 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)

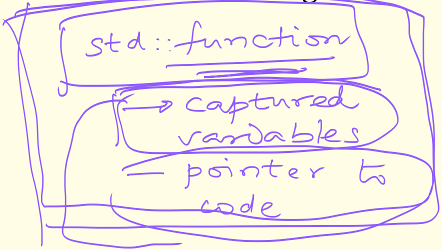

q's AR
p
p
p
q's BP
control link
control link
q's AR
p(3)'s AR
p(2)'s AR
p(1)'s AR

Supporting Closures

[ ]

```
auto f = [x] (int y) {
    return x+y
}
```

- *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<...> g(int a, float b) {
    return [a,b]() {return a+b;}
};

void p() {
    auto f = g(2,3);
    return f();   ←
}
```

```
x = y+z;

add y,z,x;
```

AST classes

- constructor
- print
- typecheck → mem_alloc()
- codegen
- eval

Exception Handling

- Example:

```
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" ;}
```

handlers

- g(-1) will print “negative value invalid”, g(16) will print “n too large”

Exception Vs Return Codes

- Exceptions are often used to communucate error values from a callee to its caller. Return values provide alternate means of communicating errors.
- Example use of exception handler:

```
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, eixting\n";
}
```

- We do not need to concern ourselves with every point in the program where an error may arise.

Exception Vs Return Codes (Continued)

```
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 */ }
}
```

- Assume that `fac` returns 0 or a negative number to indicated errors
- If return codes were used to indicate errors, then we are forced to check return codes (and take appropriate action) at every point in code.

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

Stack Allocation (Continued)

- 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.

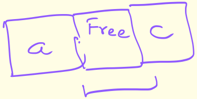
```
int fact(int n){
   if n=0 then 1
   else{
      int rv = n*fact(n-1);
      return rv;
   }
}
main(){
   fact(5);
}
```

Stack Allocation (Continued)

- 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



```
a = new
b = new
c = new
  ⋮
delete ....
d = new
```

Fragmentation

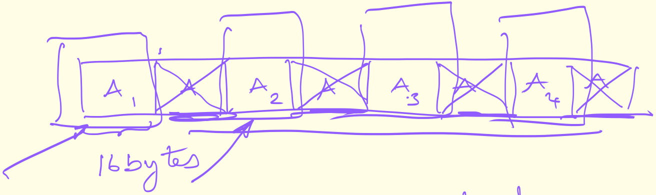
Internal fragmentation: When asked for x bytes, allocator returns $y > x$ bytes

- $y - x$ 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.

Fragmentation

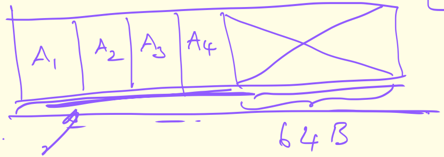


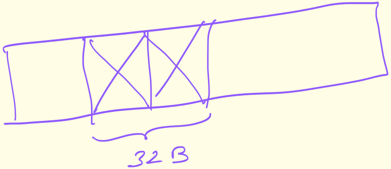
64 bytes available

Allocate 32 bytes

you cannot satisfy although 64B is available

Coalesced





Approaches for Reducing Fragmentation

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

CAR CDR

- Use bins of fixed sizes, e.g., 2^n for $n = 0, 1, 2, \ldots$
  - 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

512

~~256~~

2^k

2^{k-l}

4KB

- 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 $n > 9$

512 bytes

malloc 8 byte-aligned

Coalescing

- 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

Coalescing

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 uninitalized 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

Reference Counting (Continued)

Disadvantages:

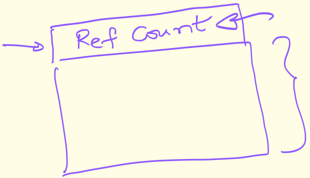
- Does not work with cyclic structures
- May impact locality
- Increases cost of each pointer update operation

Advantages:

- Overhead is predictable, fixed
- Garbage is collected immediately, so more efficient use of space

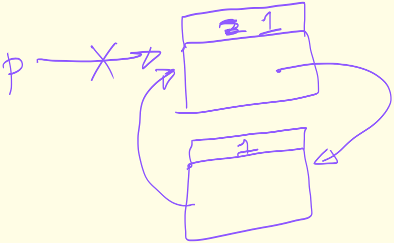
Reference Counting

How many ptrs point to this blk



Usable part of mem blk

Memory leak



p = NULL;

x = y;

incr ref count of blk ptd by y

decr ref count of blk ptd by x

Mark-and-Sweep

- Mark every allocated heap block as “unreachable” ← Init
- 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

Mark-and-Sweep

"root pointers"

- on the stack
- in global memory

DFS starting from root pointers

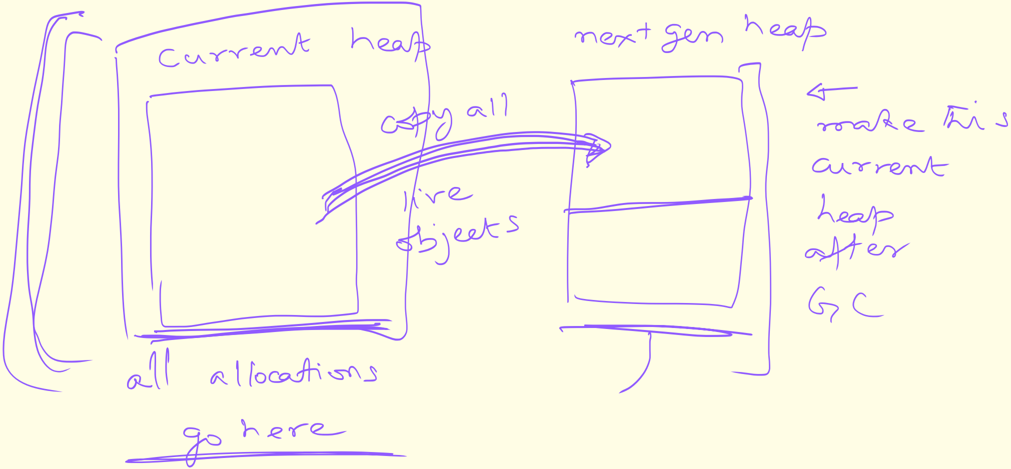
Garbage Collection Issues

- 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

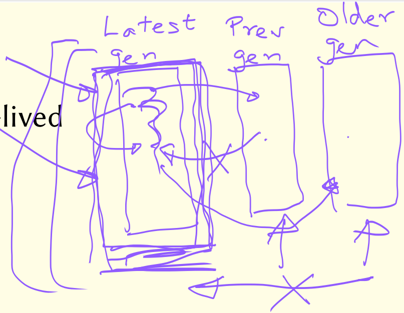
Copying Garbage Collection

- 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

Copying Garbage Collection



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

  http://java.sun.com/javase/technologies/hotspot/gc/gc_tuning_6.html

  http://www.ibm.com/developerworks/java/library/j-jtp11253/

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

Implementation Aspects of OO-Languages

- Allocation of space for data members: The space for data members is laid out the same way it is done for structures in C or other languages. Specifically:
  - The data members are allocated next to each other.
  - Some padding may be required in between fields, if the underlying machine architecture requires primitive types to be aligned at certain addresses.
  - At runtime, there is no need to look up the name of a field and identify the corresponding offset into a structure; instead, we can statically translate field names into relative addresses, with respect to the beginning of the object.
  - Data members for a derived class immediately follow the data members of the base class
  - Multiple inheritance requires more complicated handling, we will not discuss it here

Implementation Aspects of OO-Languages

```
class B {
    int i; double d;
    char c; float f; }
```

B b; → 0x8000

b.d → 0x8008

0	int i	// Integer requires 4 bytes (32-bit)
4	XXXXXXXXXXX	// pad,
8	double d	// Double requires 8 bytes (64-bit)
16	char c|XXXXX	
16	float f	// char needs 1 byte, 3 are padded
20		// float to be aligned on 4-byte
		// require 4-bytes of space

Implementation Aspects of OO-Languages

```
class C {
   int k, l; B b;
}
```

alignment requirement same as the largest alignment of any of B's fields.

0	int k
4	int l
8	int i
12	XXXXXXXXXXXX
16	double d
24	char c|XXXXX
28	float f

Implementation Aspects of OO-Languages

```
class D: public C {
   double x;
}
```

C's part

0	int k
4	int l
8	int i
12	XXXXXXXXXXXX
16	double d
24	char c|XXXXX
28	float f
32	double x

class E : public C,
public B {
}

C's part

B's part

new fields of E

new fields of D start here

Implementation of Virtual Functions

- Approach 1:
  - Lookup type info at runtime, and then call the function defined by that type.
  - Problem: very expensive, require type info to be maintained at runtime.

Implementation of Virtual Functions(Contd.)

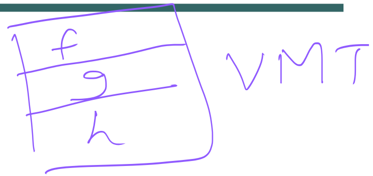
- Approach 2:
  - Treat function members like data members:
    - Allocate storage for them within the object.
    - Put a pointer to the function in this location, and translate calls to the function to make an indirection through this field.
  - Benefit:
    - No need to maintain type info at runtime.
    - Implementation of virtual methods is fast.
  - Problem:
    - Potentially lot of space is wasted for each object.
    - Even though all objects of the same class have identical values for the table.

A A::f

B B::f

Implementation of Virtual Functions(Contd.)

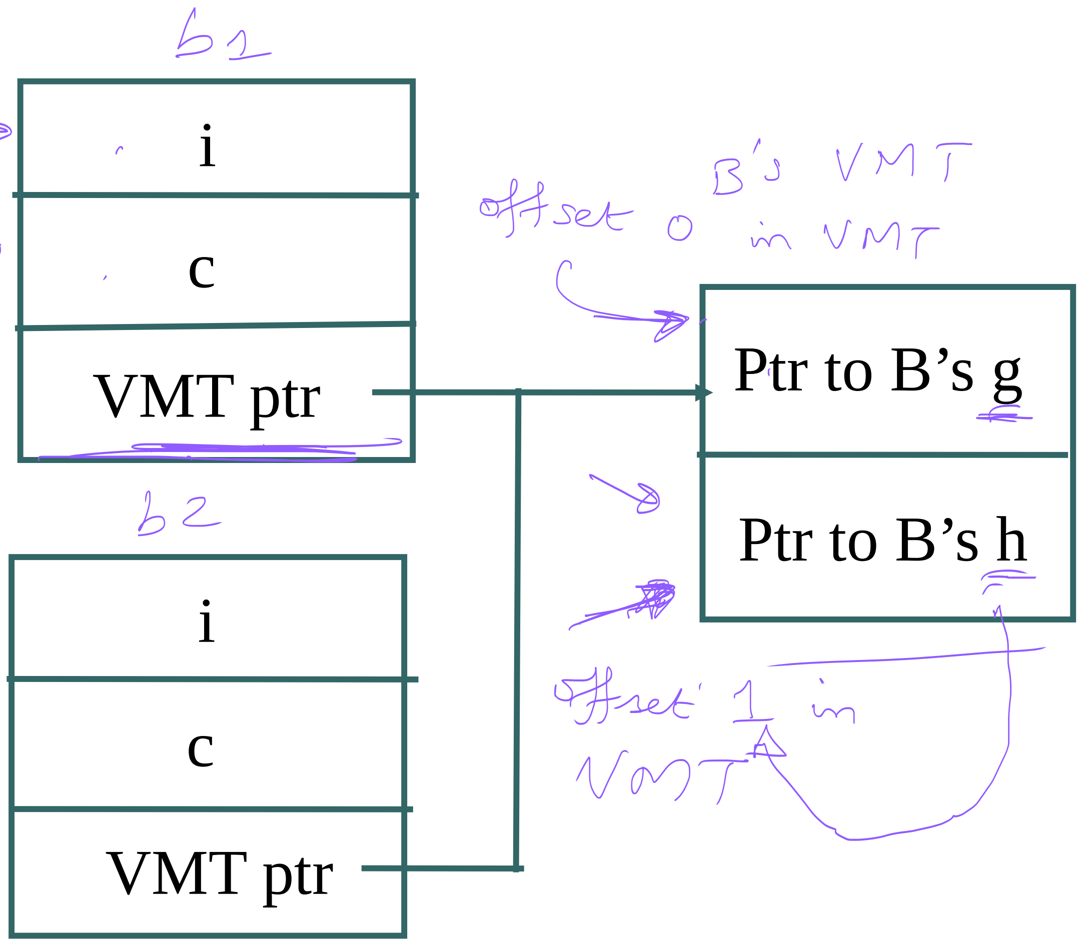
Virtual Method Table



- Approach 3:
  - Introduce additional indirection into approach 2.
  - Store a pointer to a table in the object, and this table holds the actual pointers to virtual functions.
  - Now we use only one word of storage in each object.

Implementation of Virtual Functions(Contd.)

```
class B {
    int i ;
    char c ;
    virtual void g();
    virtual void h();
  }
B b1, b2;
```



i

c

VMT ptr

i

c

VMT ptr

Ptr to B's g

Ptr to B's h

b1.h()

[(&b1+2)+1]

Impact of subtype principle on Implementation

- The subtype principle requires that any piece of code that operates on an object of type B can work "as is" when given an object belonging to a subclass of B.
- This implies that runtime representation used for objects of a subtype A must be compatible with those for objects of the base type B.
- Note that the way the fields of an object are accessed at runtime is using an offset from the start address for the object.
  - For instance, b1.i will be accessed using an expression of the form *(&b1+0), where 0 is the offset corresponding to the field i.
  - Similarly, the field b1.c will be accessed using the expression *(&b1+1)

Impact of subtype principle on Implementation (Contd.)

- an invocation of the virtual member function b1.h() will be implemented at runtime using an instruction of the form:

  call *(*(&b1+2)+1)

  - &b1+2 gives the location where the VMT ptr is located
  - *(&b1+2) gives the value of the VMT ptr, which corresponds to the location of the VMT table
  - *(&b1+2) + 1 yields the location within the VMT table where the pointer to virtual function h is stored.

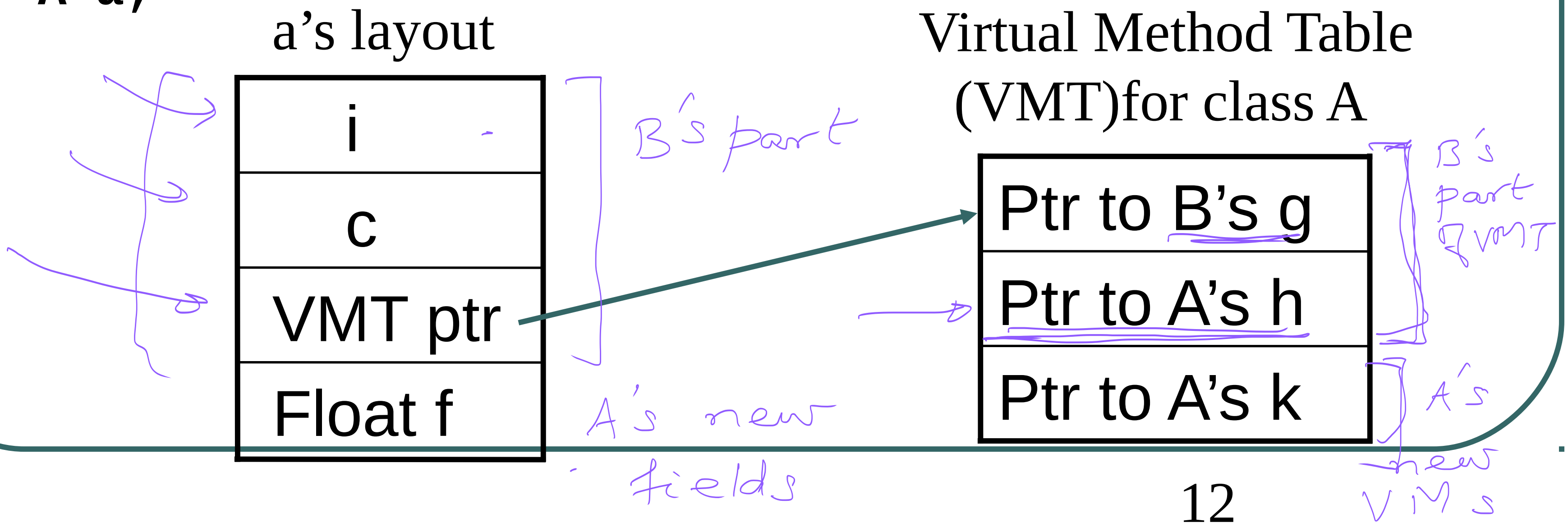
Impact of subtype principle on Implementation (Contd.)

- The subtype principle imposes the following constraint:
  - Any field of an object of type B must be stored at the same offset from the base of any object that belongs to a subtype of B.
  - The VMT ptr must be present at the same offset from the base of any object of type B or one of its subclasses.
  - The location of virtual function pointers within the VMT should remain the same for all virtual functions of B across all subclasses of B.

Impact of subtype principle on Implementation (Contd.)

- We must use the following layout for an object of type A defined as follows:

```
class A: public B {
    float f;
    void h(); // reuses implementation of G from B;
    virtual void k();}
A a;
```



a’s layout

i
c
VMT ptr
Float f

Virtual Method Table (VMT)for class A

Ptr to B’s g
Ptr to A’s h
Ptr to A’s k

Impact of subtype principle on Implementation (Contd.)

- In order to satisfy the constraint that VMT ptr appear at the same position in objects of type A and B, it is necessary for the data field f in A to appear after the VMT field.
- A couple of other points:
  - a) non-virtual functions are statically dispatched, so they do not appear in the VMT table
  - b) when a virtual function f is NOT redefined in a subclass, the VMT table for that class is initialized with an entry to the function f defined its superclass.