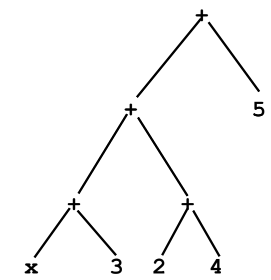
CSE 504

Expression Evaluation,
Runtime Environments

Expression evaluation

- Order of evaluation
- For the abstract syntax tree




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


Expression evaluation (Contd.)

- One possible semantics:
  - evaluate AST bottom-up, left-to-right.
- Problem:
  - constrains optimizations based on mathematical properties, e.g., commutativity and associativity
  - Consider (x+0)+(y+3)+(z+4)
  - Using associativity and commutativity, the compiler can simplify this to x+y+z+7 (3 additions at runtime)
  - A strict left-to-right evaluation would require 5 addition operations at runtime.

Expression evaluation (Contd.)

- Some languages leave order of eval 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 that allow expressions with side-effects are forced to specify order of evaluation
- Still, it is bad programming practice to use expressions where different orders of evaluation can lead to different results
  - Impacts readability (and maintainability) of programs

Evaluation of Boolean Expressions

- Left-to-right evaluation with short-circuit semantics is appropriate for boolean expressions.
  - In `e1&&e2`, `e2` is evaluated only if `e1` evaluates to true.
  - In `e1||e2`, `e2` is evaluated only if `e1` evaluates to false.
- This semantics is convenient in programming:
  - Consider statement: `if ((i<n) && a[i]!=0)`
  - With short-circuiting, `a[i]` never accessed if `i>= n`
  - Another example: `if((p!=NULL) && p->value>0)`

Switch Statement

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

- Evaluate <expr> to get value v.
- Evaluate the case that corresponds to v.
- Restrictions:
  - <value> has to be constant, of an ordinal type e.g., int
    - Why?

Implementation of Switch 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 ;
    default: s3 ; }
can be translated as
    v = e ;
    if (v == 0) s0 ;
    else if (v == 1) s1 ;
    else if (v == 2) s2 ;
    else s3 ;
```


Implementation of switch statement (Contd.)

- 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) s2 ;
else s3 ;
```

Implementation of switch statement (Contd.)

- 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 (average case).

Loops

- while:
  - Consider the statement: **`while C do S`**
  - Its semantics is equivalent to: **`if C then {S; s1}`**
- repeat:
  - Consider: **`repeat S until C`**
  - Its semantics is equivalent to **`S; if (!C) then S2`**
- for:
  - Semantics of "**`for (S2; C; S3) S`**" is the same as that of "**`S2; while C do {S; S3}`**"

Control Statements (contd.)

- 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
  - replace procedure call with the body of called procedure

Parameter-passing semantics

- Call-by-value
- Call-by-reference
- Call-by-value-result
- Call-by-need
  - Differences with macros

Call-by-value

- Evaluate the actual parameters
- Assign them to corresponding formal parameters
- Execute the body of the procedure.
- We need to ensure that the names of local variables and formal parameters of callee do not clash with the variable names visible in the caller
  - If they do, the variables in the callee should be renamed to avoid any clash.

Call-By-Value (Contd.)

- Example:

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

==>

```
main() {
  int y;
  int x =

  z = 2*x;
}
```


Call-By-Value-Result

- In addition to the steps in CBV, add:
  - assignment statements to copy values of formal parameters to actuals at the end of callee code

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

==>

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


Call-By-Reference

- Works like CBV, with one important difference:
  - l-values (rather than r-values) are passed in.

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

==>

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

- Call-by-reference supported in C++ but not C
  - Effect realized in C by explicitly passing l-values of parameters using the “&” operator

Call-by-reference (contd.)

- 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);
```


CBVR Vs CBR

- Consider

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

- With CBVR, a will have the value 4
- With CBR, a will have the value 5

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

```
int z;
void p(int x,y) {                main() {
  z = x+x+y;                       int z1;
}                     ==>
main() {                           z = (y++)+(y++)
  int y=0;                                +(y--);
  p(y++, y--);                   }
}
```


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(Contd.)

- given

```
#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:

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


Macros(Contd.)

- 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;
    z1 = 2*z;
    z = 3*z1;
   }
}
```


Difficulties in Using the 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.

```
void p(int x, int y) {
   x = x+1; y = y+2;
}
...
int a = 3; p (a, a); // a=4 or a=5?
```

  - Otherwise, relatively easy to understand.

Difficulties in Using CBR

- Aliasing can create problems.

```
int arev(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 arev(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 arev will be {4,3,3,4}.

Difficulties in Using CBN

- CBN is probably the most complicated of the parameter passing mechanisms, and can be quite confusing in several situations.
- If the actual parameter is an expression with side-effects:

```
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.

Difficulties in Using CBN(Contd.)

- If the same variable is used in multiple parameters.
- `void swap(int x, int y) {`

```
            int tp = x;
            x = y;
            y = x;
}
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 {0, 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)

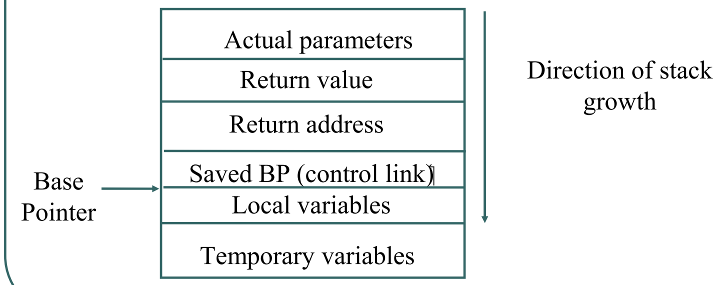
- **Static area** allocated at load/startup time.
  - Examples: global/static variables
  - Variables mapped to absolute addresses at compile time
- **Stack area** for execution-time data that obeys a last-in first-out lifetime rule.
  - Examples: local variables, parameters, temporary vars
- **Heap area** for "fully dynamic" data, i.e. data that doesn’t obey LIFO rule.
  - Examples: objects in Java, lists in Scheme.

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 (depending on its properties)
    - ARs go on the stack.

Stack Allocation

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



Simple stack-based allocation

- 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
```

- Example:

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


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
  - 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 [FP+k], parameters using [FP-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
  - 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).
- 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.

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; }
```

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

Implementation Aspects of OO-Languages

```
class C {
    0
   int k, l; B b;
}
    4

    8

    12

    16
```

int k
int l
int i
XXXXXXXXXXX
double d
char c|XXXXX
float f

Implementation Aspects of OO-Languages

```
class D: public C {
    0
   double x;
}
    4

    8

    12

    16

    24
```

int k
int l
int i
XXXXXXXXXXX
double d
char c|XXXXX
float f
double x

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.)

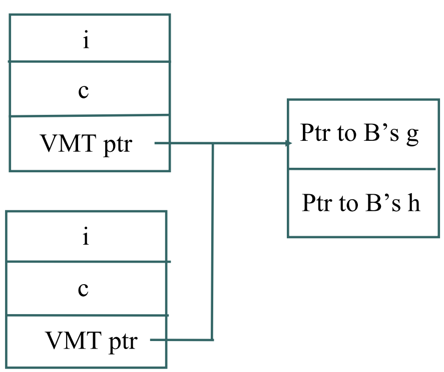
- Approach 2:
  - Treat function members like data members:
    - Allocate storage for them within the object.
    - Put a pointer to the function in this location, and translate calls to the function to make an indirection through this field.
  - Benefit:
    - No need to maintain type info at runtime.
    - 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.

Implementation of Virtual Functions(Contd.)

- 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;
```



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.

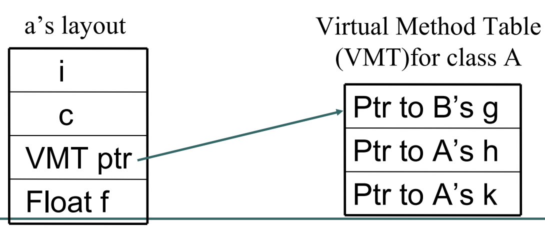
Impact of subtype principle on Implementation (Contd.)

- 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;
```



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.