TDDD16 Compilers and Interpreters

TDDB44 Compiler Construction

# Memory Management and Run-Time Systems

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## Run-Time Systems Support Program Execution

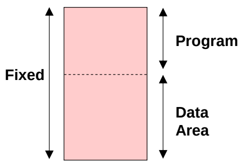
- Memory management of a program during execution. This includes allocation and de-allocation of memory cells.
- Address calculation for variable references.
- For references to non-local data, finding the right object taking scope into consideration.
- Recursion, which means that several instances of the same procedure are active (activations of a procedure) at the same time during execution.
- Dynamic language constructs, such as dynamic arrays, pointer structures, etc.
- Different sorts of parameter transfer

Two different memory management strategies: **static** and **dynamic** memory management, determined by the language to be executed.



## Static Memory Management

- All data and its size must be known during compilation, i.e. the memory space needed during execution is known at compile-time.
- The underlying language has no recursion.
- Data is referenced to by absolute addresses.




- Static memory management needs no run-time support, because everything about memory management can be decided during compilation.
- An example of such a language is FORTRAN77, whereas FORTRAN90 has recursion.



## Dynamic Memory Management (1)

- Data size is not known at compiler time (e.g. dynamic arrays, pointer structures)
- There is recursion
- Examples of such languages are: Pascal, C, Algol, Java,



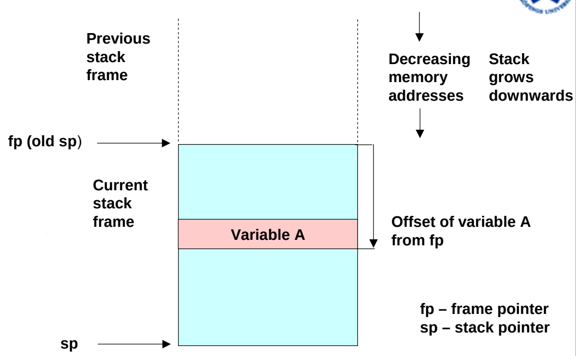
## Dynamic Memory Management (2) Run-Time Support

Run-Time support is needed for languages with dynamic memory management:

- The call chain must be stored somewhere and references to non-local variables must be dealt with.
- Variables can not be referenced by absolute addresses, but by <*blockno, offset*>.
- All data belonging to a block (procedure) is gathered together in an *activation record (stack frame)*.
- At a procedure call memory is allocated on the stack and each call involves constructing an activation record.



## A Stack Frame with Frame and Stack Pointers



## Some Concepts (Rep.)

- **Activation**
  - Each call (execution) of a procedure is known as **activation** of the procedure.
- **Life span of an activation**
  - The life span of an activation of a procedure p lasts from the execution's first statement to the last statement in p's procedure body.
- **Recursive procedure**
  - A procedure is recursive if it can be activated again during the life span of the previous activation.
- **Activation tree**
  - An activation tree shows how procedures are activated and terminated during an execution of a program.
  - Note that a program can have different activation trees in different executions.
- **Call chain**
  - All current activations (ordered by activation time)
  - - a path in the activation tree
  - - a sequence of procedure frames on the run-time stack

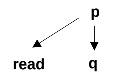


## Example of Activation Tree (Rep.)

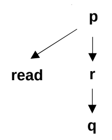
```
program p;
 procedure q;
  ...
  end (* q *);

  procedure r;
  ...
   q;
  end (* r *);

begin (* p *)
  read(x);
  if x = 0
   then q;
   else r;
end (* p *);
```

**Two different activation trees for the program:**

Activation tree when x=0




Activation tree when x≠0






## Formal and Actual Parameters (Rep.)

- Arguments declared in the head of a procedure declaration are its **formal** parameters and arguments in the procedure call are its **actual** parameters.
- In the example below:
  i: is a formal parameter
  k: is an actual parameter

```
procedure A(i: integer);
begin (* A *)
 ...
 A(k);
 ...
end (* A *);
```



## Activation Record

**All information which is needed for an activation of a procedure is put in a record which is called an activation record. The activation record remains on the stack during the life span of the procedure. An activation record contains:**

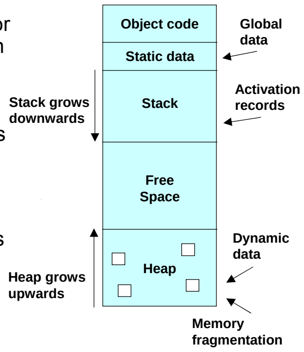
- Local data
- Temporary data
- Return address
- Parameters
- Pointers to previous activation records (*dynamic link*, *control link*)
- *Static link* (*access link*) or *display* for finding the correct references to non-local data (e.g. in enclosing scopes)
- Dynamically allocated data (*dope vectors*)
- Space for a return value (where needed)
- Space for saving the contents of registers

```
procedure p1
  var A: ...
  procecure p2
    ... reference A
  end (* p2 *)
end (* p1 *)
```



## Typical Memory Organization (Pascal/Java-like language)

- **Static data**
  - The memory requirement for data objects must be known at compile time and the address to these objects is not changed during execution, so the addresses can be hard-coded in the object code.
- **Stack**
  - Space for activation records is allocated for each new activation of procedures.
- **Heap**
  - Allocation when necessary.






## How are non-local variables referenced?

- Static link (access link)
- Display

**Example:**

```
program prog;        (* Block B0,predefined vars)
var a,b,c: integer;  (* Block B1,  Globals*)
procedure p1;
  var b, c: real;    (* Block B2 *)
  procedure p2;
    var c: real;     (* Block B3 *)
    begin
      c := b+a;      (* B3.c := B2.b + B1.a *)
    end (* p2 *);
  begin
    p2;
  end (* p1);
begin
  p1;
end (* prog *).
```

**In the procedures the variables are referenced using <blockno, offset>:**

`B3.c := B2.b + B1.a`

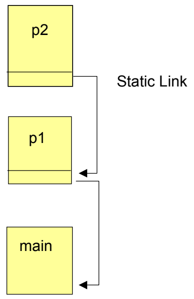
**or by using relative blocknumber:**

`0.c := 1.b + 2.a`

**(0: current block, 1: nearest surrounding block, etc.)**

## Non-local references through Static Link

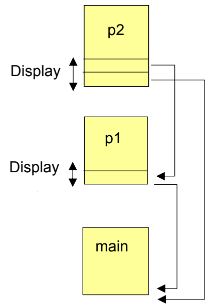
- The static link is a pointer to the most recent activation record for the **textually surrounding** block
- Example. Use relative block number for statement inside procedure p2:
  `0.c := 1.b + 2.a`
  For variable a follow the static link 2 steps.
- This method is practical and uses little space. With deeply nested procedures it will be slow.






## Non-local references through Display

- Display is a table with pointers (addresses) to surrounding procedures' activation records.
- The display can be stored in the activation records.
- Display is faster than static link for deep nesting, but requires more space.
- Display can be slightly slower than static link for very shallow nesting.

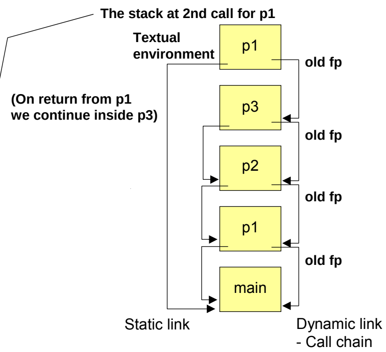





## Dynamic Link, i.e., Control Link

- Dynamic link specifies the call chain,
- Not the same as static link if there is a recursive call chain,e.g

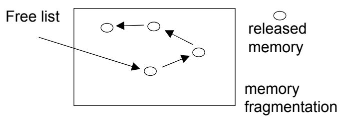
```
program foo;
  procedure p1;
    procedure p2
      procedure p3;
      begin (* p3*)
          p1;
          ...
      end (* p3 *);
    begin (* p2 *)
        p3;
        ...
    end (* p2 *)
  begin (* p1 *)
    p2;
    ...;
  end (* p1)
begin (* main *)
  p1;
end (* main *)
```






## Heap Allocation (Rep.)

- In some languages data can dynamically be built during execution and its size is not known (e.g. strings of variable length, lists, tree structures, etc).
- Manual memory management
  - De-allocation is **not** performed automatically as in stack allocation. Hard work, can lead to bugs.
  - Pascal: **new(p)** (*allocation*) **dispose(p)** (* deallocation*)
    C: **p=malloc()** (*allocation*) **free(p)** (* deallocation*)
- Automatic memory management, with garbage collection (e.g. Lisp, Java)
  - De-allocation is automatic. Resource-consuming, but avoids bugs.




**After memory compaction:**




## Data Storage and Referencing

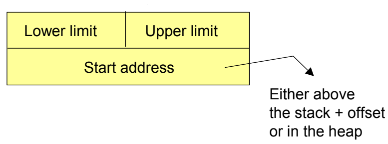
- **Where is data stored and how is it referenced?**
  - (Semi-static) Static data can be allocated directly (consecutive in the activation record, data area).
  - Data is referenced by <*blockno, offset*>. *blockno* is specified as **nesting depth**.
- **Simple variables (boolean, integer, real** ...)
  - These have a fixed size and are put directly into the activation record, or in registers.
- **Static arrays**
  - Fixed number of elements, i.e. size is known at compile time.
    Example: `A: array[1..100] of integer;`
  - Stored directly in the activation record.



## Dynamic Arrays

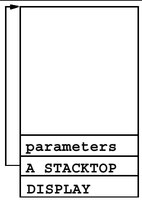
- The size is unknown at compile time:
  - Example: `B: array[1..max] of integer;`
  - `max` not known at compile time.
- *Dope vector* (*data descriptor*) is used for dynamic arrays. Dope vectors are stored in the activation record.

Dope vector:

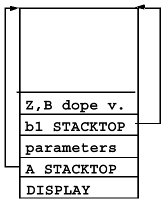


## Dynamic Arrays and Block Structures in ALGOL (1)

```
PROCEDURE A(X,Y); INTEGER X, Y;
 L1: BEGIN  REAL Z;                    (block B1:)
           ARRAY B[X:Y];
     L2: BEGIN REAL D,E;
     L3:    •••
             END;

     L4: BEGIN ARRAY A[1:X];
            L5: BEGIN REAL E;
            L6:    •••
                 END;
     L7: END;
 L8: END;
```



before L1

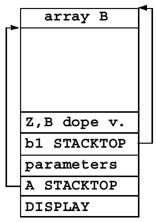


before L2

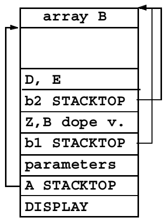


## Dynamic Arrays and Block Structures in ALGOL (2)

```
PROCEDURE A(X,Y); INTEGER X, Y;
 L1: BEGIN REAL Z;                 (bloc
          ARRAY B[X:Y];
     L2:BEGIN REAL D,E;
     L3:    •••
          END;

     L4:BEGIN ARRAY A[1:X];
          L5:BEGIN REAL E;
          L6:    •••
               END;
     L7: END;
 L8: END;
```



L2,L4,L8

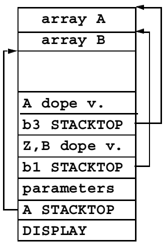


L3

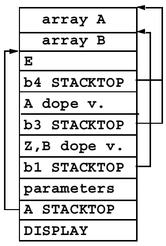


## Dynamic Arrays and Block Structures in ALGOL (3)

```
PROCEDURE A(X,Y); INTEGER X, Y;
 L1: BEGIN REAL Z;                 (blo
          ARRAY B[X:Y];
     L2:BEGIN REAL D,E;
     L3:    •••
          END;

     L4:BEGIN ARRAY A[1:X];
          L5:BEGIN REAL E
          L6:    •••
               END;
     L7: END;
 L8: END;
```



L5, L7



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## Parameter Passing (1) (Rep.) Call by Reference

- There are different ways of passing parameters in different programming languages. Here are four of the most common methods:
- *1. Call by reference (Call by location)*
  - The address to the actual parameter, *l-value*, is passed to the called routine's AR
  - The actual parameter's value can be changed.
  - Causes aliasing.
  - The actual parameter must have an l-value.
- Example: Pascal's **VAR** parameters, reference parameters in C++. In Fortran, this is the only kind of parameter.



## Parameter Passing (2) (Rep.) Call by Value

- *2. Call by value*
  - The value of the actual parameter is passed
  - The actual parameter cannot change value
- Example: Pascal's non-**VAR** parameters, found in most languages (e.g. C, C++, Java)



## Parameter Passing (3) (Rep.) *Call by value-result* (hybrid)

- *3. Call by value-result* (hybrid)
  - The value of the actual parameter is calculated by the calling procedure and is copied to AR for the called procedure.
  - The actual parameter's value is not affected during execution of the called procedure.
  - At return the value of the formal parameter is copied to the actual parameter, if the actual parameter has an l-value (e.g. is a variable).
- Found in Ada.

## Parameter Passing (4) (Rep.) Call by Name

- *4. Call by name*
  - Similar to macro definitions
  - No values calculated or passed
  - The whole expression of the parameter is passed as a procedure without parameters, a *thunk*.
  - Calculating the expression is performed by evaluating the thunk each time there is a reference to the parameter.
  - Some unpleasant effects, but also general/powerful.
- Found in Algol, Mathematica, Lazy functional languages



## Example of Using the Four Parameter Passing Methods: (Rep.)

```
procedure swap(x, y : integer);    ...
var temp : integer;                i := 1;
begin                              a[i]:=10;  (* a: array[1..5]
  temp := x;                                     of integer *)
  x := y;                          print(i,a[i]);
  y := temp;                       swap(i,a[i]);
end (*swap*);                      print(i,a[1]);
```

**Results from the 4 parameter passing methods**
**Printouts from the print statements in the above example**

| Call by reference | Call by value | Call by value-result | Call by name |
|---|---|---|---|
| 1 10 | 1 10 | 1 10 | 1 10 |
| 10 1 | 1 10 | 10 1 | Error! |



## Reason for the Error in the Call-by-name Example

The following happens:

```
x = text('i');
y = text('a[i]');

temp := i;       (* => temp:=1 *)
i := a[i];       (* => i:=10 since a[i]=10 *)
a[i] := temp;    (* => a[10]:=1 =>   index out of bounds *)
```

Note: This error does not occur in lazy functional languages using call-by-name since side-effects are not allowed.



## Static Memory Management E.g. Fortran77 and (partly) CUDA/C on NVIDIA

- No procedure nesting, i.e., no block structure.
  - ⇒ References to variables locally or globally.
  - ⇒ No displays or static links needed.
- No recursion ( ⇒ stack not needed).
- All data are static ( ⇒ heap not needed).
- All memory is allocated **statically**
  - ⇒ variables are referenced by absolute address.
  - The data area (i.e. the activation record) is often placed with the code.
  - Inefficient for allocating space for objects which are perhaps used only a short time during execution.
  - But execution is efficient in that all addresses are placed and ready in the object code



## Static Memory Allocation and Procedure Call/Return for Fortran77

```
SUBROUTINE SUB(J)
I = 1
J = I+3*J
END
```

| |
|---|
| Return address |
| I |
| J |
| Temp |
| ...<br>Code for SUB<br>... |

- **At procedure call**
  1. Put the addresses (or values) of the actual parameters in the data area.
  2. Save register contents.
  3. Put return address in the data area.
  4. Execute the routine.
- **On return:**
  1. Re-set the registers.
  2. Jump back.



## Memory management in Algol, Pascal, C, C++, Java

- **Language Properties**:
  - Nested procedures/blocks (PASCAL, ALGOL)
  - Dynamic arrays (ALGOL, C++, Java, ...)
  - Recursion
  - Heap allocation (PASCAL, C, C++, Java, ...)
- **Problems:**
  - References to non-local variables (solved by display or static link)
  - Call-by-name (ALGOL, Lazy Functional Languages)
  - Dynamic arrays (*dope vector*)
  - Procedures as parameters

## Events when Procedure P Calls Q

**At call:**

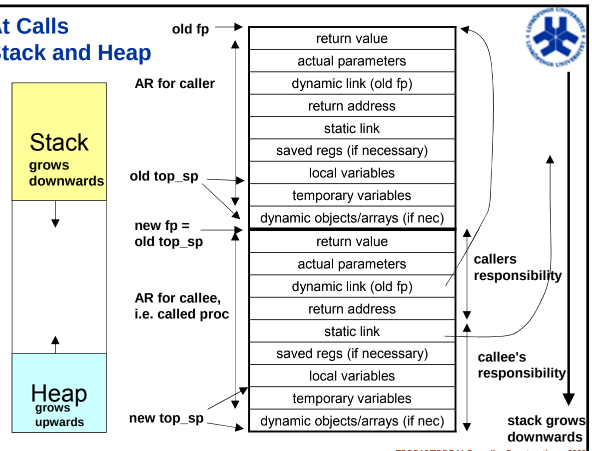
- P already has an AR (activation record) on the stack
- P's responsibility:
  - Allocate space for Q's AR.
  - Evaluate actual parameters and put them in Q's AR.
  - Save return address and dynamic links (i.e. top_sp) in new (Q's) AR.
  - Update (increment) top_sp.
- Q's responsibility:
  - Save register contents and other status info.
  - Initialise own local data and start to execute.

**At return:**

- Q's responsibility
  - Save return value in own AR (NB! P can access the return value after the jump).
  - Reset the dynamic link and register contents, ...
  - Q finishes with return to P's code.
- P's Responsibility
  - P collects the return value from Q, despite update of top-sp.



## At Calls
## Stack and Heap






## Procedure Call/Return in Algol, Pascal, C, ...

**At call:**

1. Space for activation record is allocated on the stack.
2. Display / static link is set.
3. Move the actual parameters.
4. Save implicit parameters (e.g. registers).
5. Save return address.
6. Set dynamic link.
7. Execute the routine.

**At return:**

1. Reset dynamic link.
2. Reset the registers
3. Reset display / static link
4. Jump back.