Subprograms

Programming Languages

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Outline

- Process Abstraction
- Activation Records
- Executing Subprograms
- Nested Subprograms
- Referencing Environments

Process Abstraction

Overarching Goal

Generalize program execution to the degree that we do with data structures (Abstract Data Types)

1. Every subprogram has exactly **one** entry point
2. A *calling subprogram* (caller) is suspended during the execution of the *called subprogram* (callee)
3. Control will **always return** to the caller when the callee terminates

Process Abstraction

1. Every subprogram has exactly **one** entry point

- Typically called `main`
  - Java: `public static void main(String[])`
  - C/C++: `int main()` or `int main(int, char**)`
  - C#: `static (void/int) Main([string[]])`
  - D: `(void/int) main([string[]])`
  - Go: `func main()` (as part of main package)
- Implicitly the execution environment in others
  - F#: `[<EntryPoint>]` annotation
  - Python: can check `__name__ == "__main__"`

Process Abstraction

2. A ***calling subprogram*** (caller) is suspended during the execution of the ***called subprogram*** (callee)

```
main () {
  int x;
  x = add (3, 4);
  print (x);
}
```

Begin execution of main

Process Abstraction

2. A *calling subprogram* (caller) is suspended during the execution of the *called subprogram* (callee)

```
main () {
   int x;
   x = add (3, 4);
   print (x);
}
```

`main` is the **caller**
`add` is the **callee**

Prepare to call add – still within main

Process Abstraction

2. A *calling subprogram* (caller) is suspended during the execution of the *called subprogram* (callee)

```
add (int x, int y) {
  int res;
  res = x + y;
  return res;
}
```

main is the **caller**
add is the **callee**

Call add. “Pause” execution of main.

Process Abstraction

2. A *calling subprogram* (caller) is suspended during the execution of the *called subprogram* (callee)

```
add (int x, int y) {
   int res;
   res = x + y;
   return res;
}
```

`main` is the **caller**
`add` is the **callee**

Continue execution of add

Process Abstraction

2. A *calling subprogram* (caller) is suspended during the execution of the *called subprogram* (callee)

```
add (int x, int y) {
   int res;
   res = x + y;
   return res;
}
```

main is the **caller**
add is the **callee**

End execution of add. “Return” back to caller

Process Abstraction

3. Control will **always return** to the caller when the callee terminates

```
add (int x, int y) {
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main is the **caller**
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End execution of add. “Return” back to caller

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add is the **callee**

Continue execution of main

Process Abstraction

What do we need to keep track of in order to guarantee the process execution abstraction?

Process Abstraction

What do we need to keep track of in order to guarantee the process execution abstraction?

- Where we will (eventually) return to
- Parameters
- Local variables

New Concept: *Activation Record*

Activation Record

Return Address

- Where we will (eventually) return to

Parameters

- Data explicitly passed to the callee from the caller

Local Variables

- Data created within the callee
- Includes **all** blocks (statically determined)

Activation Record

Return Address

- Where we will (eventually) return to **[code]**

Dynamic Link

- *Which Activation Record to return to* **[data]**

Parameters

- Data explicitly passed to the callee from the caller

Local Variables

- Data created within the callee
- Includes **all** blocks (statically determined)

Activation Record: Caller Semantics

Return Address

save where we are in the code

Dynamic Link

save the current activation record

Parameters

pass all parameters to the callee

~~**Local Variables**~~

Transfer control to callee

Activation Record: Callee Semantics

~~Return Address~~

~~Dynamic Link~~

Parameters

read values during execution

Local Variables

make space for all local variables

Begin execution of code

Activation Record: Return Semantics

Return Address

Restore prior code location

Dynamic Link

Restore prior activation record

Parameters

update reference parameters during execution

Local Variables

clear the created space

Transfer control to caller once done

Executing a Subprogram

Executing a Program

Two Main Parts

- **Code**
  - The actual program being executed
  - What the programmer wrote (but the computer understands via compilation / interpreting)
- **Data**
  - The information created/modified/destroyed during the lifetime of the program execution
  - Also known as !code

Executing a Program


```
int a(int x) {
  int y = x;
  y *= y;
  return y;
}
int b(int x, int y) {
  int z = a(x);
  z += y;
  return z;
}
int main() {
  int i = a(4);
  int j = b(i, 5);
  return j;
}
```

main	locals	i
		j

Executing a Program

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

Code

Data

```
  return j;
}
```

Executing a Program


```
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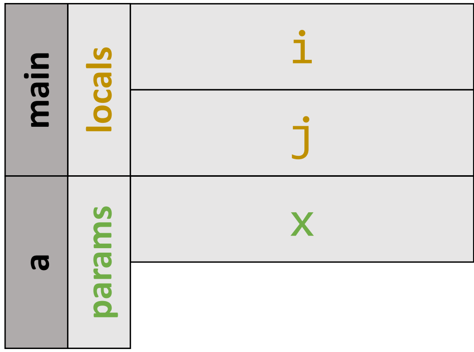
Activation Record:

- **Parameters**
- Return Address (**code**)
- Dynamic Link (**data**)
- **Locals**



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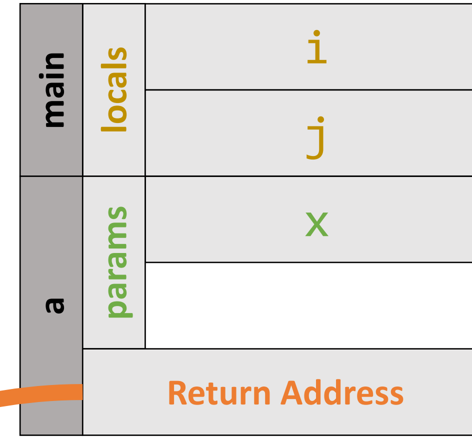


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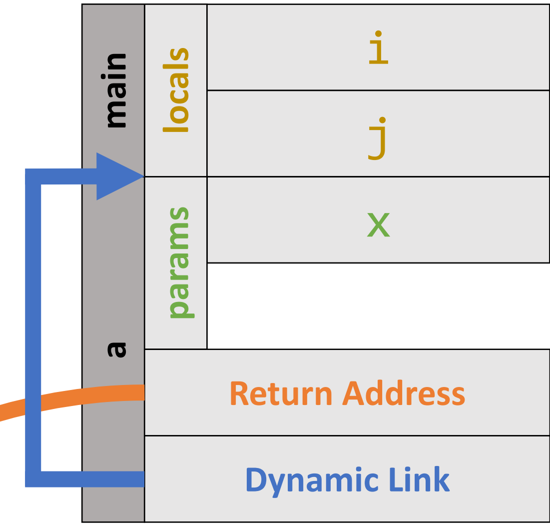
Executing a Program

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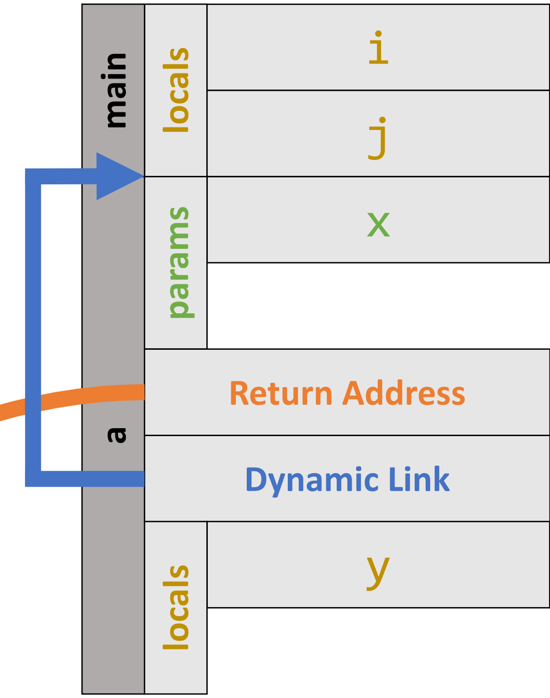

Activation Record:

- **Parameters**
- Return Address (**code**)
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Executing a Program

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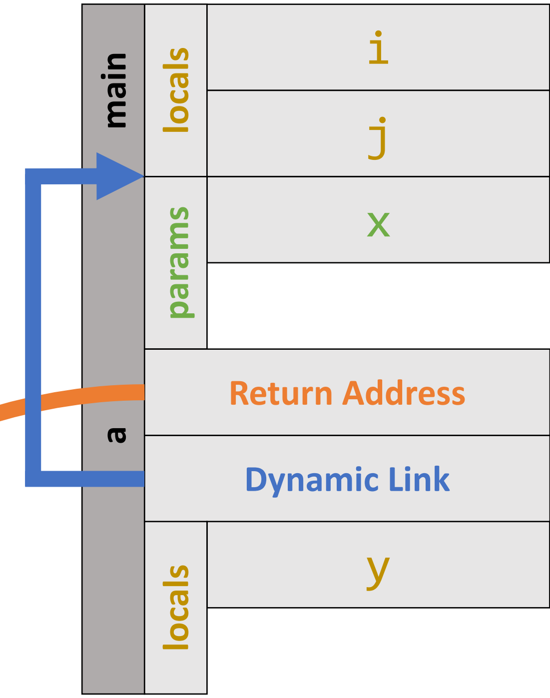

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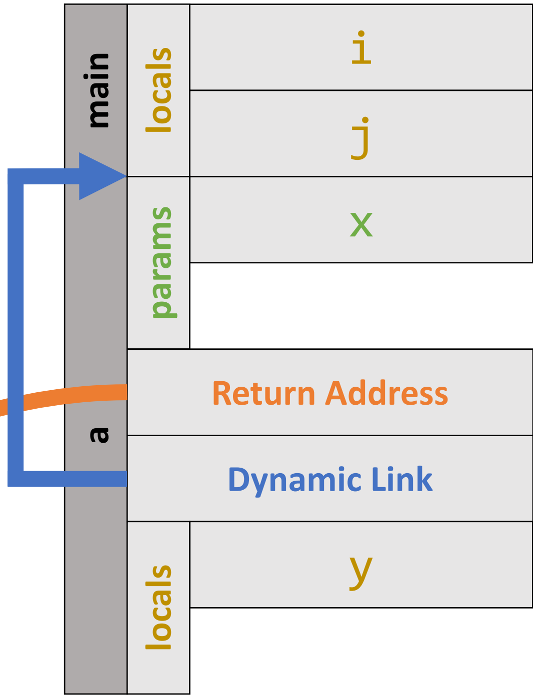

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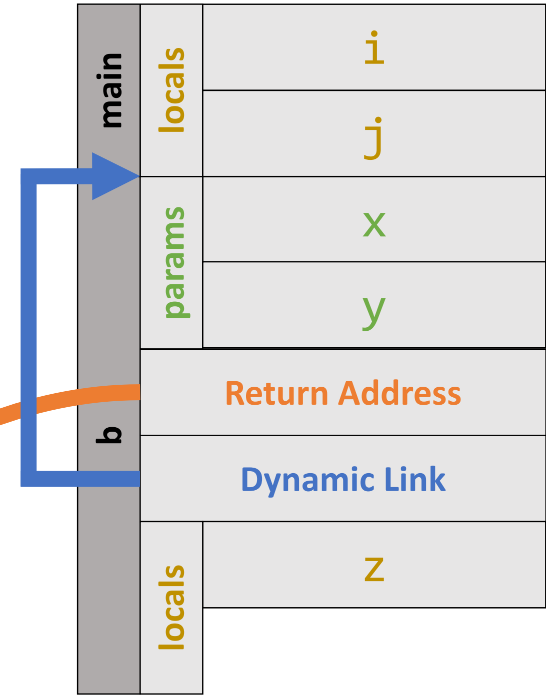

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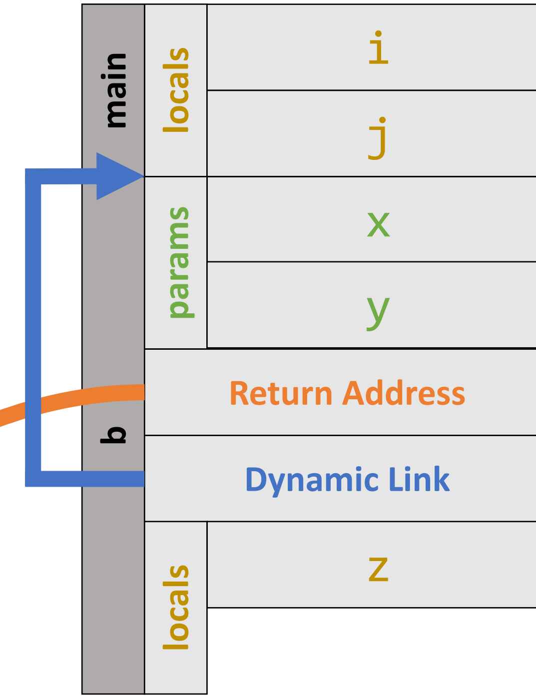

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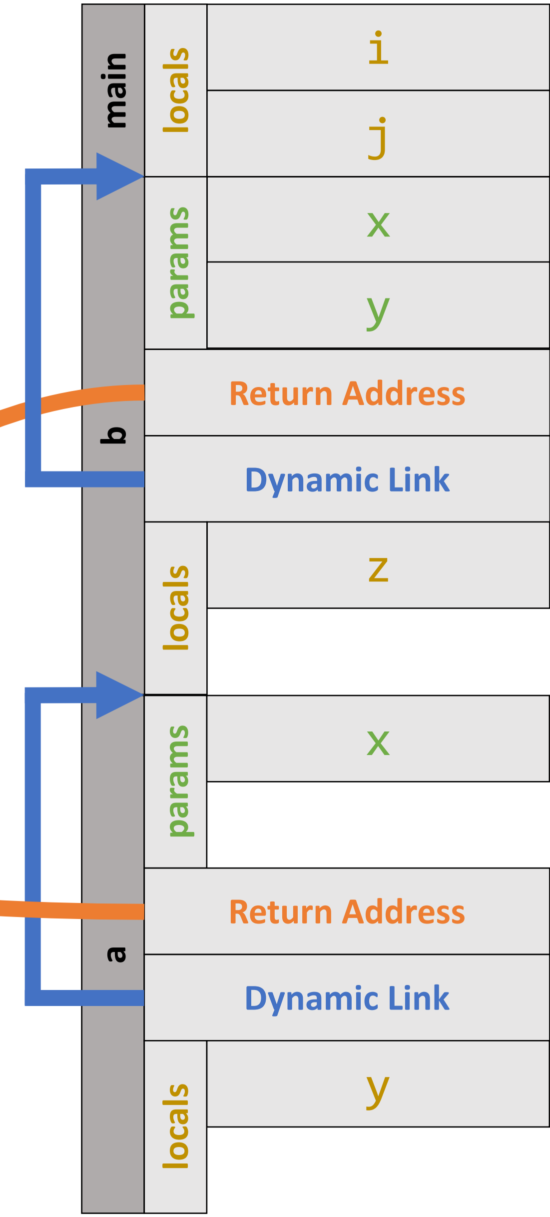

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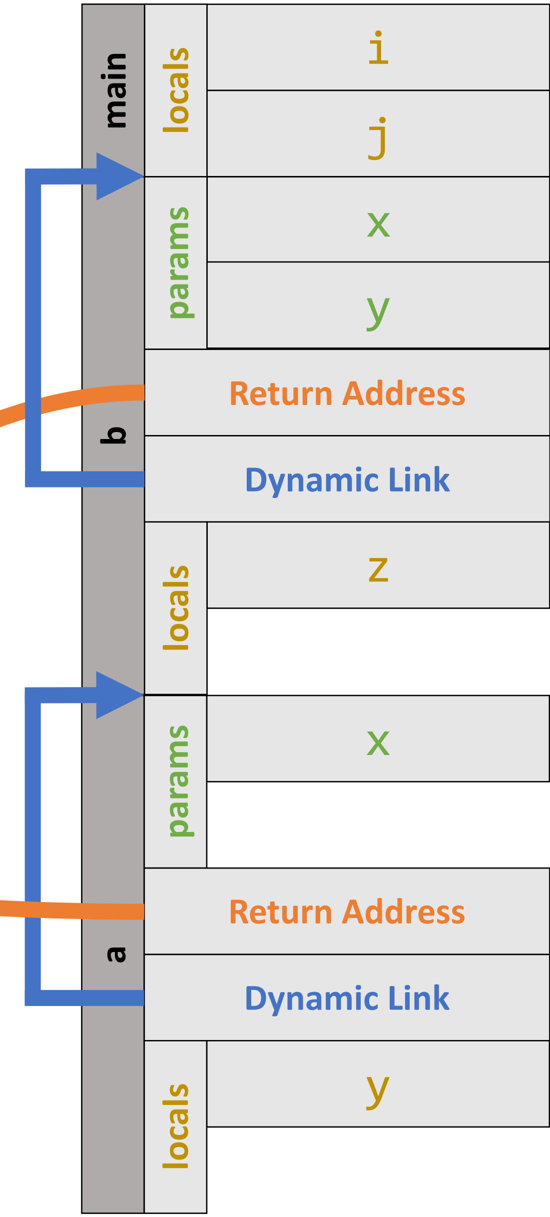

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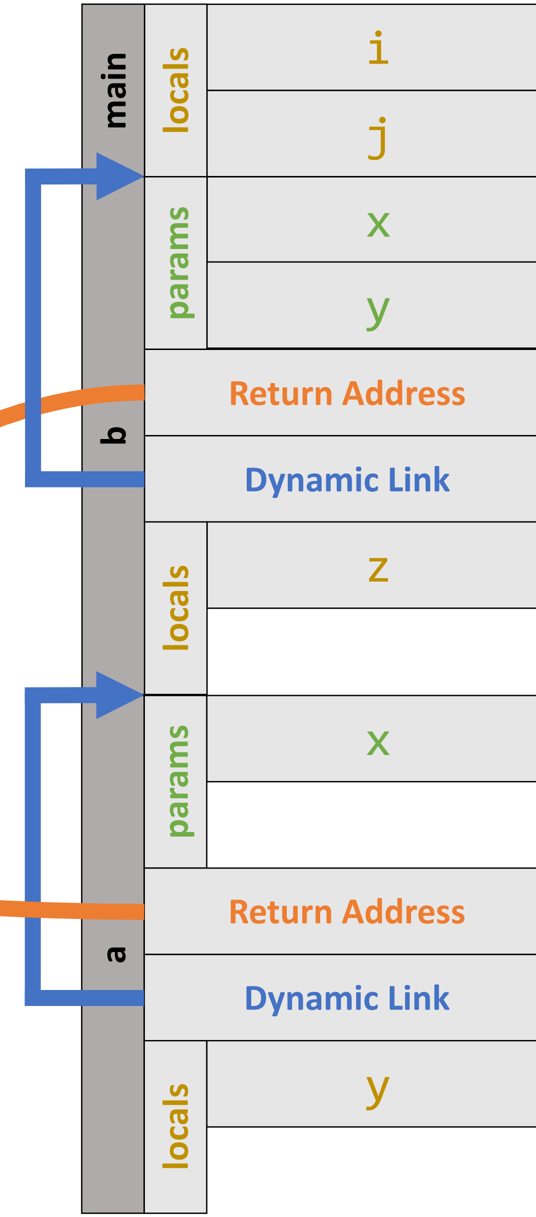

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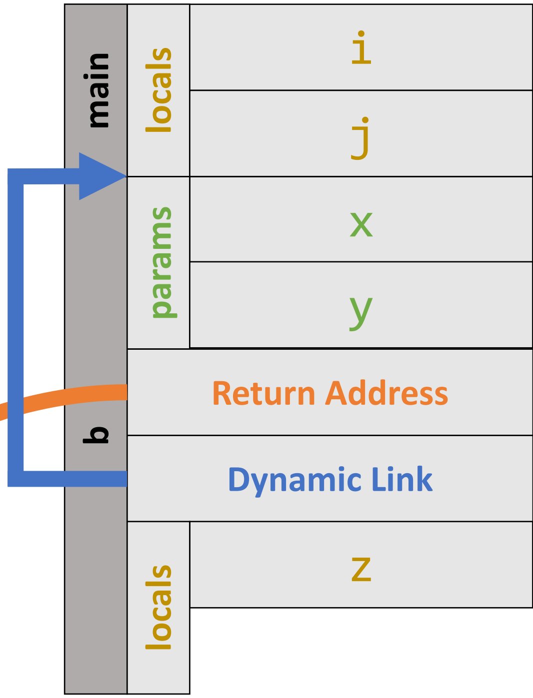

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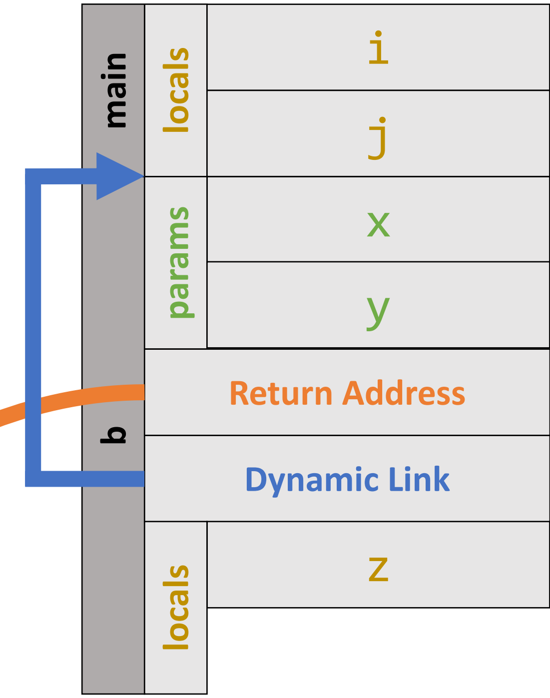

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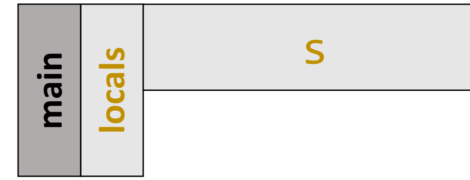
Executing a Subprogram

Recursive Example

Recursion?




```
int fact(int x) {
  int res = x;
  if (res <= 1) {
    return 1;
  }
  res *= fact(x - 1);
  return res;
}

int main() {
  int s = fact(2);
  printf ("%d\n", s);
}
```

Recursion?

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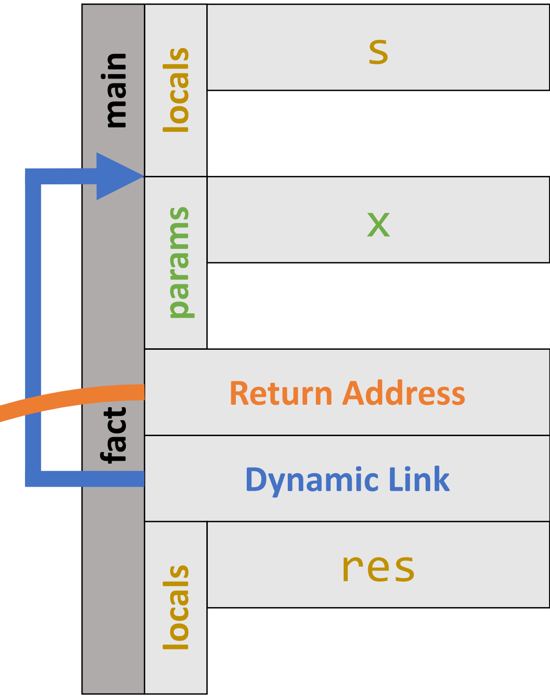

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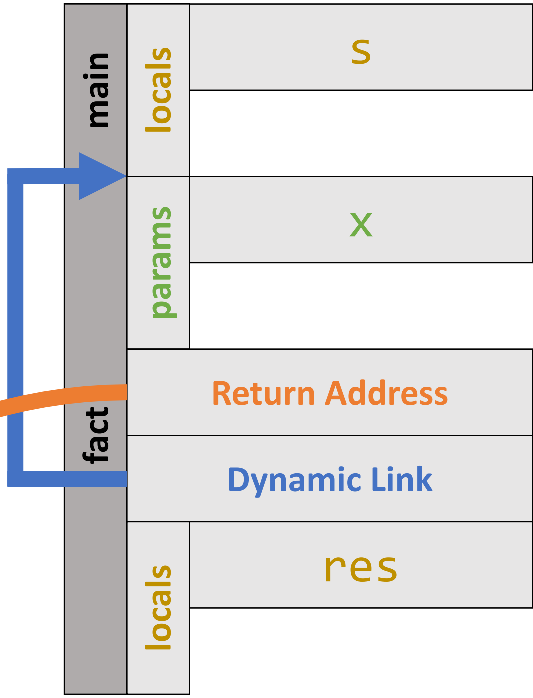

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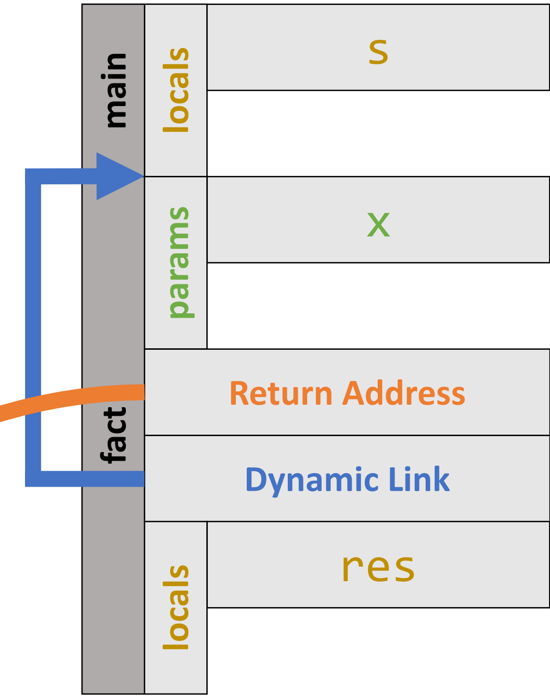

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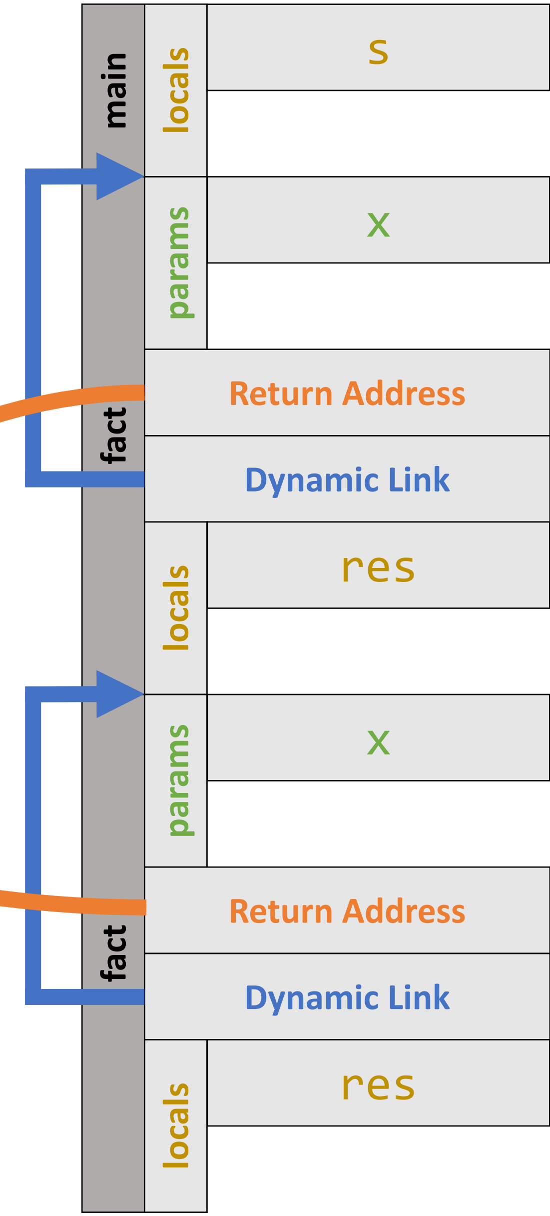

Recursion?

```c
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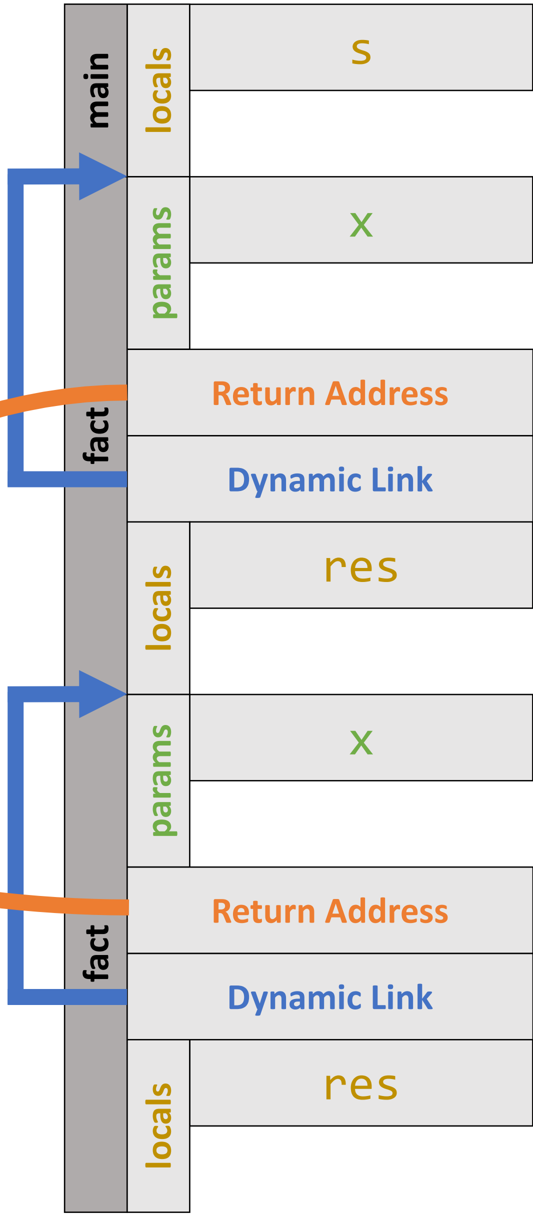

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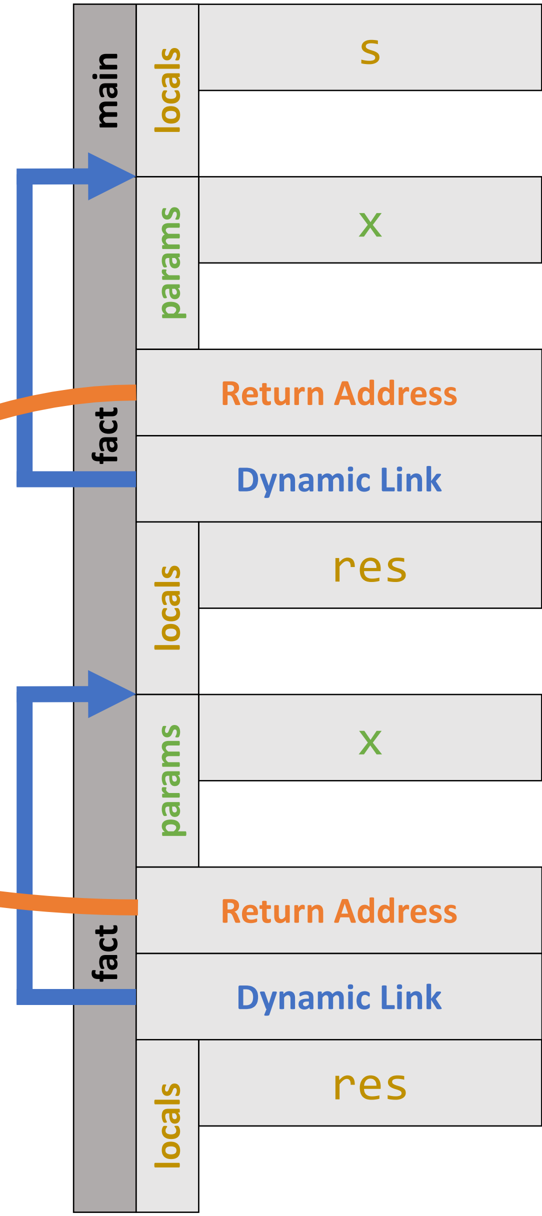

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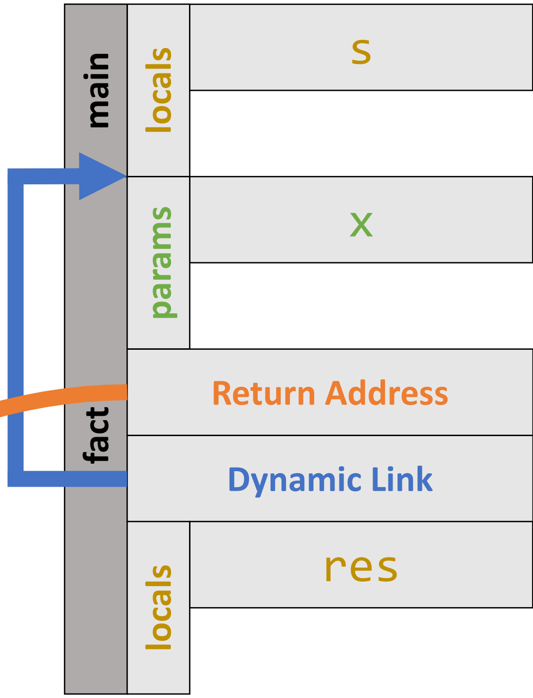

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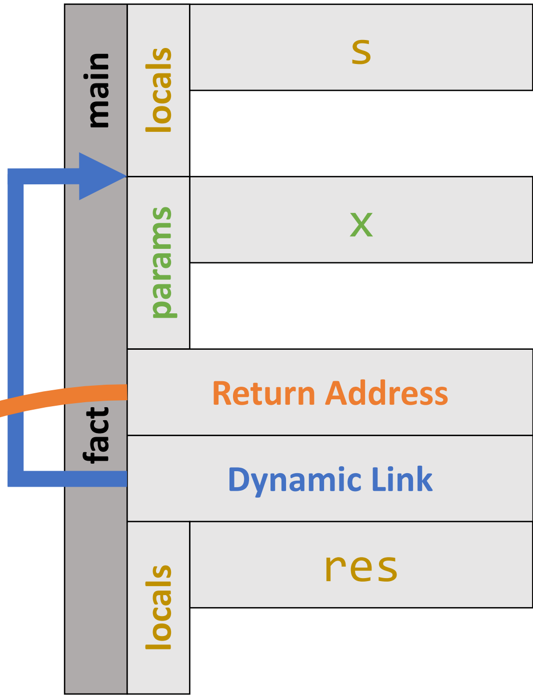

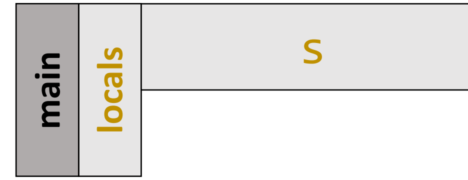

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}
```

Nested Subprograms

- A subprogram is considered **nested** when it is defined within another subprogram

```
function f () {
    function g() {
        return 1;
    }
    return g() + g();
}
```

Nested Subprograms: Issues

- Mathematically pure subprograms (*functions*) introduce no issues
- **Non-local references** must be resolved (e.g. x)

```
function f () {
    int x = 4;
    function g() {
        return x * 2;
    }
    return g() + g();
}
```

Nested Subprograms

Locating a Non-Local Reference

1. Find the correct activation record instance

   The most "recent" activation record containing a reference with a specific name

2. Determine the correct variable offset within the selected activation record instance.

   This is easily determined by the local variable ordering

Nested Subprograms

Two Approaches to Non-Local Reference Resolution

1. **Static Scoping**

   Create and manage a static chain. The static chain is a list of our ancestors.

2. **Dynamic Scoping**
   - Deep Access

     Scan the dynamic link chain
   - Shallow Access

     Maintain a central "stack" of names to references

Static Scoping

At a function call the activation record needs to include an additional piece of information: **static link**

The **static link** will refer to the **most recent** activation record instance of the *static parent*

This means we need to scan the dynamic chain!

Static Scoping Problems

- Non-local references are **slow** when the nesting depth is large
- Cost of non-local references is difficult/impossible to determine
- Simple code changes can alter/change the nesting depth (which changes the performance!)

Static Scoping Example

```
function main(){
  var x;
  function bigsub() {
    var a, b, c;
    function sub1() {
      var a, d;
      a = b + c; // PLACE 1
    }
    function sub2(x) {
      var b, e;
      function sub3() {
        var c, e;
        sub1();
        e = b + a; // PLACE 2
      }
      sub3();
      a = d + e; // PLACE 3
    }
    sub2(7);
  }
  bigsub();
}
```

```
static relationship:
main
- bigsub
  - sub1
  - sub2
    - sub3
```

```
dynamic call chain:
main
bigsub
sub2
sub3
sub1
```

Static Scoping Example

```
function main(){
  var x;
  function bigsub() {
    var a, b, c;
    function sub1() {
      var a, d;
      a = b + c; // PLACE 1
    }
    function sub2(x) {
      var b, e;
      function sub3() {
        var c, e;
        sub1();
        e = b + a; // PLACE 2
      }
      sub3();
      a = d + e; // PLACE 3
    }
    sub2(7);
  }
  bigsub();
}
```

Dynamic Scoping

Deep Access

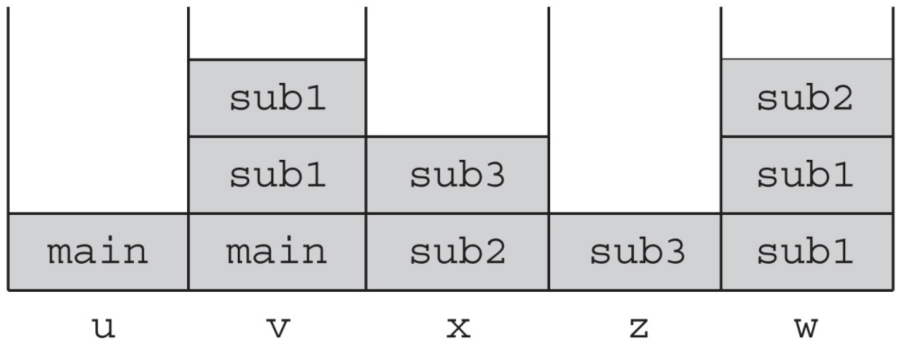
Scan the dynamic link chain

Every activation record instance tracks names

Shallow Access

Central location for all names

One stack required for each name




```
void sub3() {
  int x, z;
  x = u + v;
  …
}
void sub2() {
  int w, x;
  …
}
void sub1() {
  int v, w;
  …
}
void main() {
  int v, u;
  …
}
```

Dynamic Scoping Example

```
function main(){
  var x;
  function bigsub() {
    var a, b, c;
    function sub1() {
      var a, d;
      a = b + c; // PLACE 1
    }
    function sub2(x) {
      var b, e;
      function sub3() {
        var c, e;
        sub1();
        e = b + a; // PLACE 2
      }
      sub3();
      a = d + e; // PLACE 3
    }
    sub2(7);
  }
  bigsub();
}
```