PP5 and TAC

- **Goal:** Generate TAC IR for Decaf programs.
- We provide a code generator to produce MIPS assembly.
  - You can run your programs using **`spim`**, the MIPS simulator.
- You must also take care of some low-level details:
  - Assign all parameters, local variables, and temporaries positions in a stack frame.
  - Assign all global variables positions in the global memory segment.
  - Assign all fields in a class an offset from the base of the object.

An Important Detail

- When generating IR at this level, you do **not** need to worry about optimizing it.
- It's okay to generate IR that has lots of unnecessary assignments, redundant computations, etc.

Three-Address Code

- Or "**TAC**"
- The IR that you will be using for the final programming project.
- High-level assembly where each operation has at most three operands.
- Uses explicit runtime stack for function calls.
- Uses vtables for dynamic dispatch.

Sample TAC Code

```
int x;
int y;

int x2 = x * x;

int y2 = y * y;
int r2 = x2 + y2;
```

```
x2 = x * x;

y2 = y * y;
r2 = x2 + y2;
```

Sample TAC Code

```
int a;
int b;
int c;
int d;

a = b + c + d;
b = a * a + b * b;
```

```
_t0 = b + c;
a = _t0 + d;
_t1 = a * a;
_t2 = b * b;
b = _t1 + _t2;
```

Sample TAC Code

```
int a;
int b;

a = 5 + 2 * b;
```

TAC allows for instructions with two operands.

```
_t0 = 5;
_t1 = 2 * b;
a = _t0 + _t1;
```

Simple TAC Instructions

- **Variable assignment** allows assignments of the form
  - `var = constant;`
  - var_1 `=` var_2`;`
  - var_1 `=` var_2 **`op`** var_3`;`
  - var_1 `= constant` **`op`** var_2`;`
  - var_1 `=` var_2 **`op`** `constant;`
  - `var =` $constant_1$ **`op`** $constant_2$`;`
- Permitted operators are **`+`**, **`-`**, **`*`**, **`/`**, **`%`**.
- How would you compile **`y = -x;`** ?

`y = 0 - x;` **`y = -1 * x;`**

One More with **`bool`**s

```
int x;
int y;
bool b1;
bool b2;
bool b3;

b1 = x + x < y
b2 = x + x == y
b3 = x + x > y
```

```
_t0 = x + x;
_t1 = y;
b1 = _t0 < _t1;

_t2 = x + x;
_t3 = y;
b2 = _t2 == _t3;

_t4 = x + x;
_t5 = y;
b3 = _t5 < _t4;
```

TAC with **bool**s

- Boolean variables are represented as integers that have zero or nonzero values.
- In addition to the arithmetic operator, TAC supports **<**, **==**, **||**, and **&&**.
- How might you compile **b = (x <= y)** ?

```
_t0 = x < y;
_t1 = x == y;
b = _t0 || _t1;
```

Control Flow Statements

```
int x;
int y;
int z;

if (x < y)
   z = x;
else
   z = y;

z = z * z;
```

```
    _t0 = x < y;
    IfZ _t0 Goto _L0;
    z = x;
    Goto _L1;
_L0:
    z = y;
_L1:
    z = z * z;
```

Labels

- TAC allows for **named labels** indicating particular points in the code that can be jumped to.
- There are two control flow instructions:
  - **Goto *label*;**
  - **IfZ *value* Goto *label*;**
- Note that **IfZ** is always paired with **Goto**.

Control Flow Statements

```
int x;
int y;

while (x < y)
          { x =
   x * 2;
}

y = x;
```

```
_L0:
    _t0 = x < y;
    IfZ _t0 Goto _L1;
    x = x * 2;
    Goto _L0;
_L1:
    y = x;
```

A Complete Decaf Program

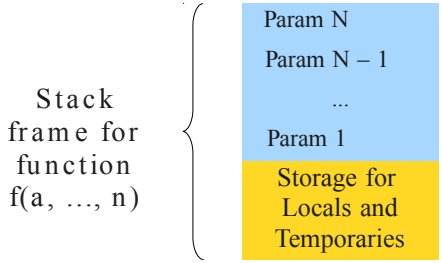
```
void main() {
   int x, y;
   int m2 = x * x + y * y;

   while (m2 > 5)
         = m2 - x;
      { m2
}  }
```

```
main:
   BeginFunc 24;
   _t0 = x * x;
   _t1 = y * y;
   m2 = _t0 + _t1;
_L0:
   _t2 = 5 < m2;
   IfZ _t2 Goto _L1;
   m2 = m2 - x;
   Goto _L0;
_L1:
   EndFunc;
```

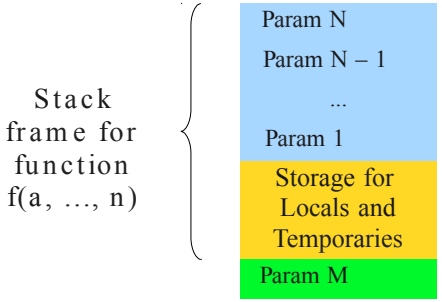
Compiling Functions

- Decaf functions consist of four pieces:
  - A **label** identifying the start of the function.
    - *(Why?)*
  - A **BeginFunc *N*;** instruction reserving **N** bytes of space for locals and temporaries.
  - The body of the function.
  - An **EndFunc;** instruction marking the end of the function.
    - When reached, cleans up stack frame and returns.

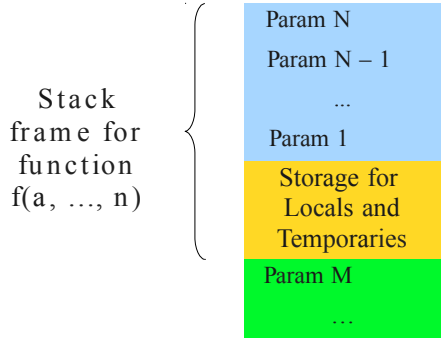
A Logical Decaf Stack Frame



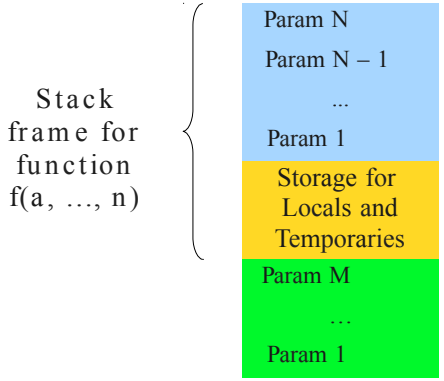
A Logical Decaf Stack Frame



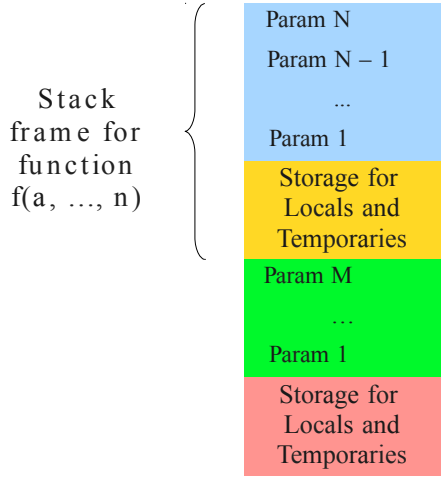
A Logical Decaf Stack Frame



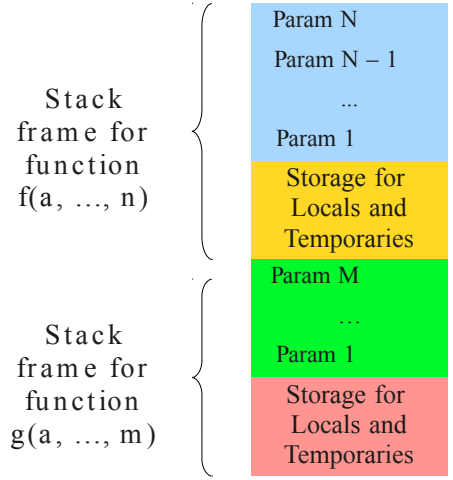
A Logical Decaf Stack Frame



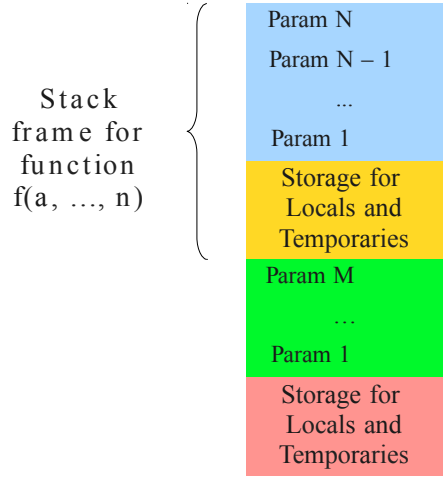
A Logical Decaf Stack Frame



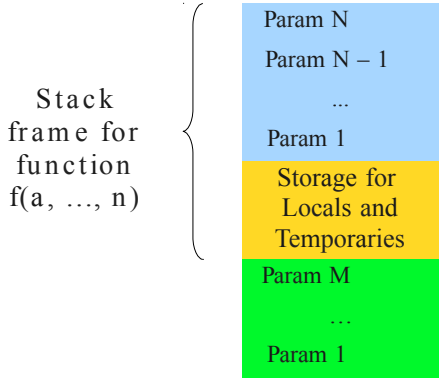
A Logical Decaf Stack Frame



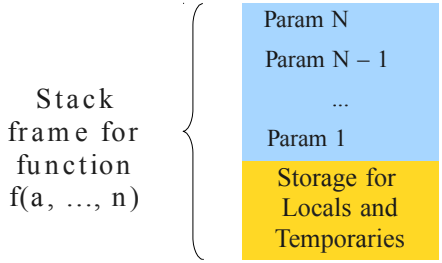
A Logical Decaf Stack Frame



A Logical Decaf Stack Frame



A Logical Decaf Stack Frame



Compiling Function Calls

```
void SimpleFn(int z) {
    int x, y;
    x = x * y * z;
}

void main()
   { SimpleFunction(137
   );
}
```

```
_SimpleFn:
    BeginFunc 16;
    _t0 = x * y;
    _t1 = _t0 * z;
    x = _t1;
    EndFunc;
```

Compiling Function Calls

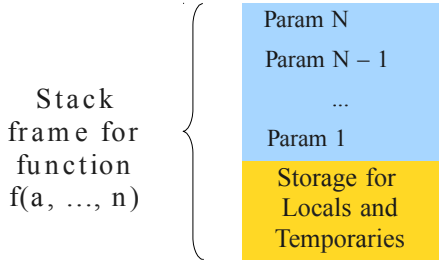
```
void SimpleFn(int z) {
    int x, y;
    x = x * y * z;
}

void main()
   { SimpleFunction(137
   );
}
```

```
_SimpleFn:
    BeginFunc 16;
    _t0 = x * y;
    _t1 = _t0 * z;
    x = _t1;
    EndFunc;

main:
    BeginFunc 4;
    _t0 = 137;
    PushParam _t0;
    LCall _SimpleFn;
    PopParams 4;
    EndFunc;
```

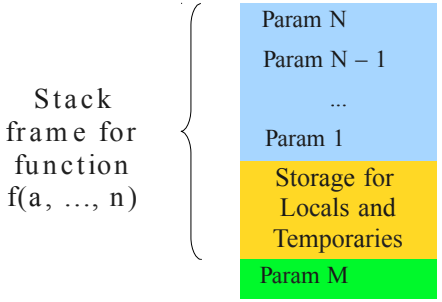
Stack Management in TAC

- The **BeginFunc *N;*** instruction only needs to reserve room for local variables and temporaries.
- The **EndFunc;** instruction reclaims the room allocated with **BeginFunc *N;***
- A single parameter is pushed onto the stack by the caller using the **PushParam *var*** instruction.
- Space for parameters is reclaimed by the caller using the **PopParams *N;*** instruction.
  - ***N*** is measured in *bytes*, not number of arguments.

A Logical Decaf Stack Frame

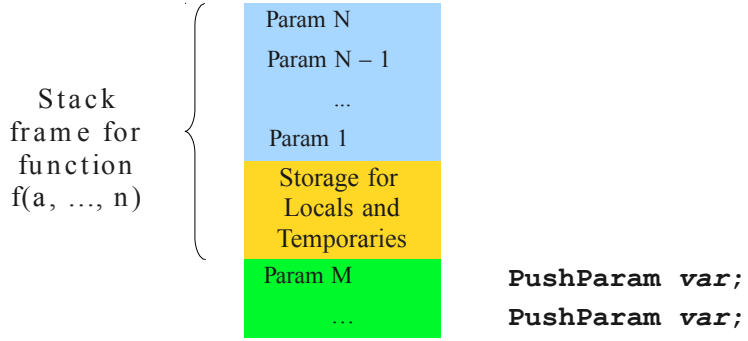


A Logical Decaf Stack Frame



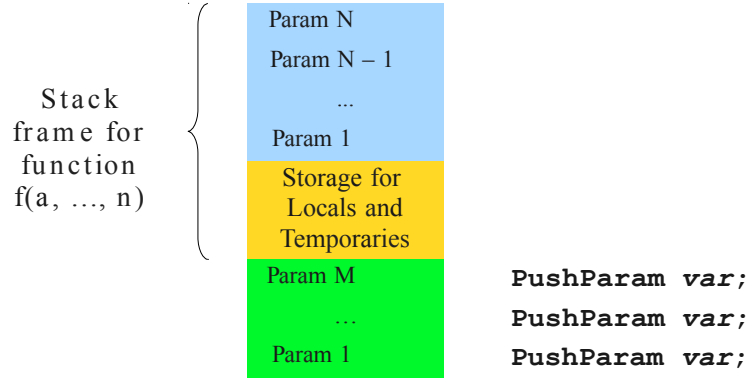

```
PushParam var;
```

A Logical Decaf Stack Frame



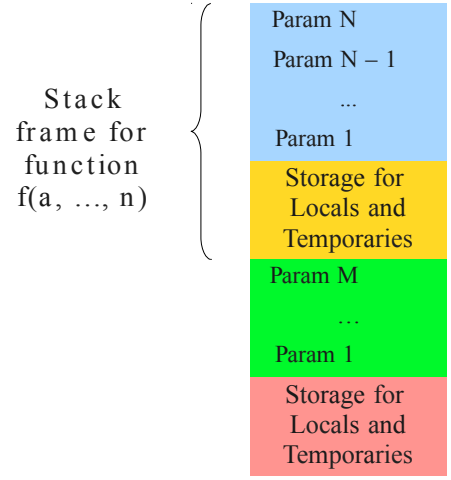

```
PushParam var;
PushParam var;
```

A Logical Decaf Stack Frame



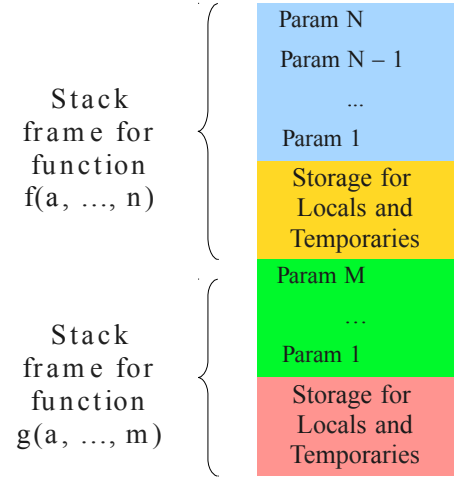

```
PushParam var;
PushParam var;
PushParam var;
```

A Logical Decaf Stack Frame



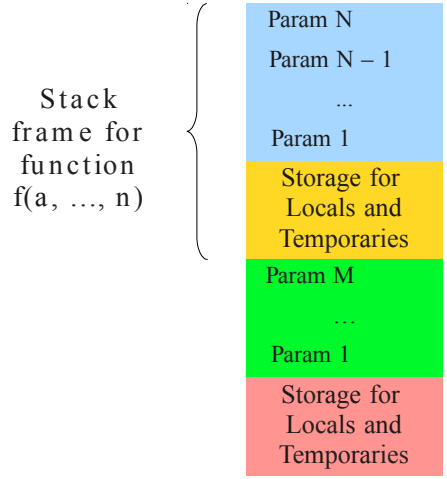

```
PushParam var;
PushParam var;
PushParam var;
BeginFunc N;
```

A Logical Decaf Stack Frame

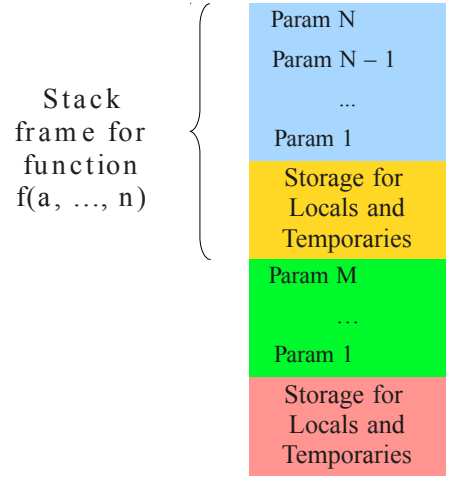



```
PushParam var;
PushParam var;
PushParam var;
BeginFunc N;
```

A Logical Decaf Stack Frame

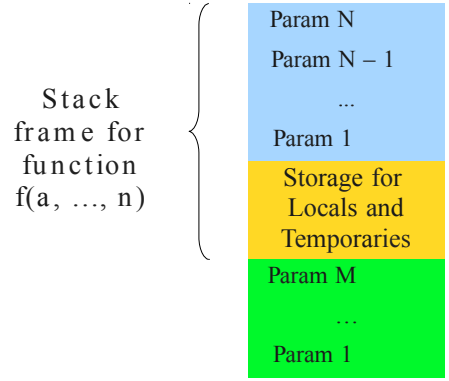


A Logical Decaf Stack Frame

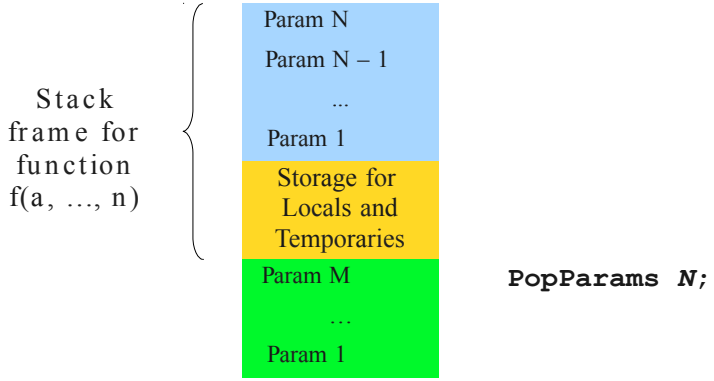



```
EndFunc;
```

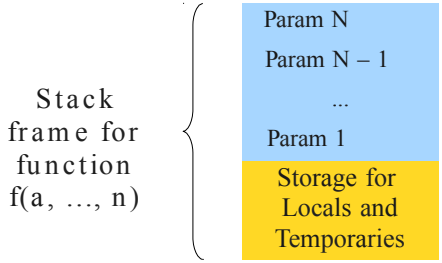
A Logical Decaf Stack Frame



A Logical Decaf Stack Frame



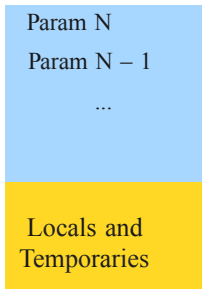
A Logical Decaf Stack Frame



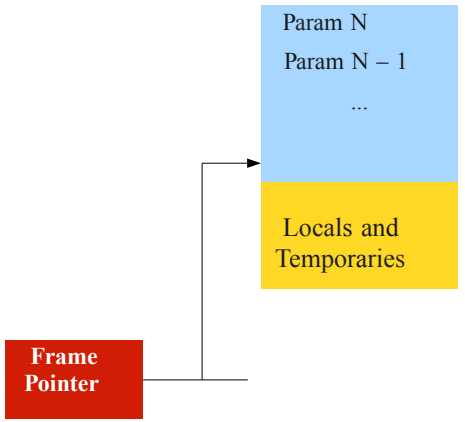
Storage Allocation

- As described so far, TAC does not specify where variables and temporaries are stored.
- For the final programming project, you will need to tell the code generator where each variable should be stored.
- This normally would be handled during code generation, but Just For Fun we thought you should have some experience handling this. ☺

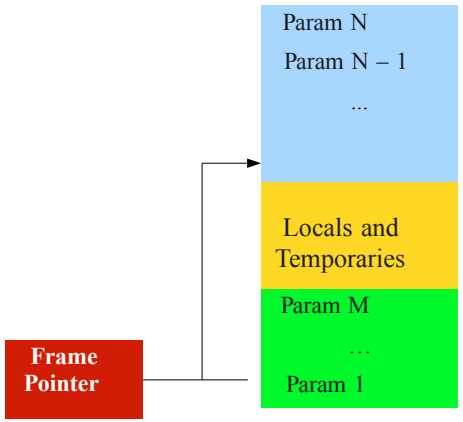
The Frame Pointer



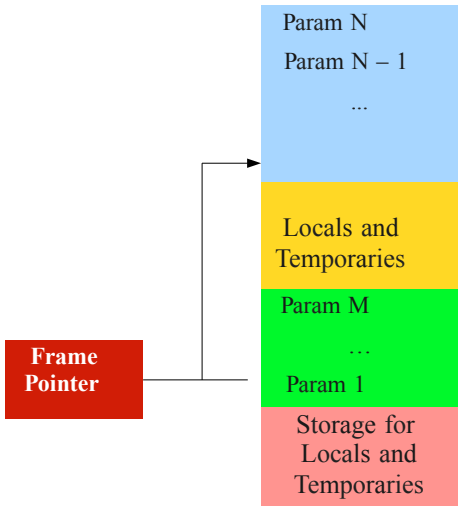
The Frame Pointer



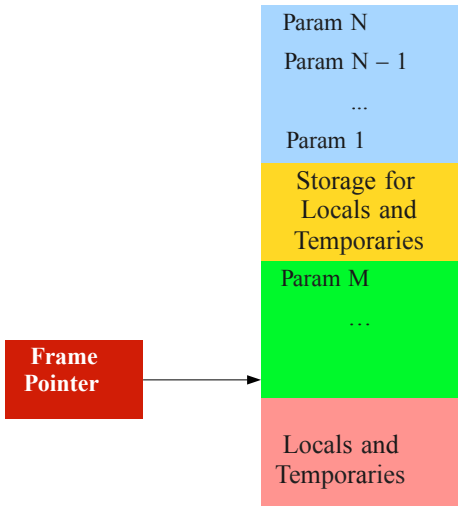
The Frame Pointer



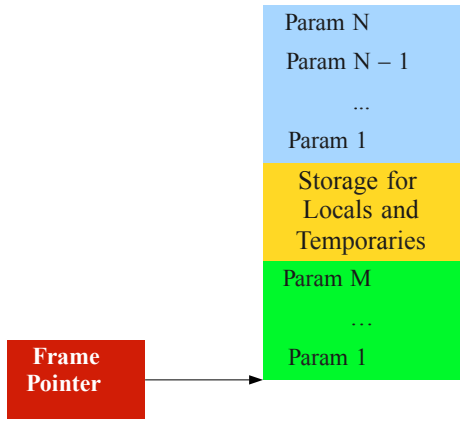
The Frame Pointer



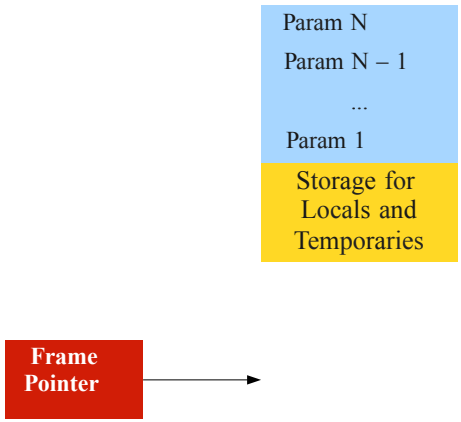
The Frame Pointer



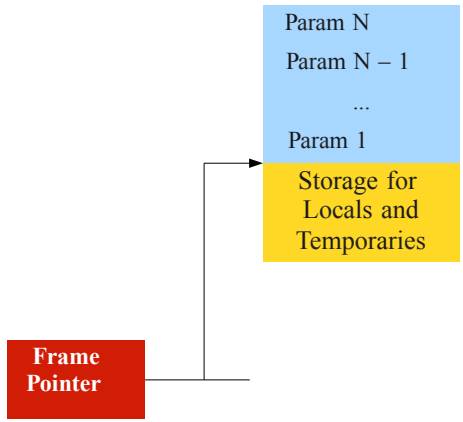
The Frame Pointer



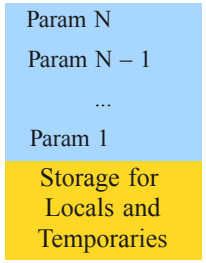
The Frame Pointer



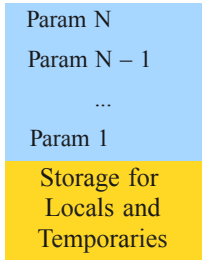
The Frame Pointer

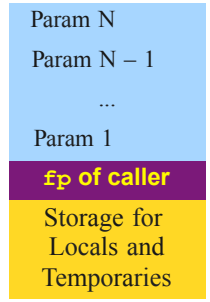


Logical vs Physical Stack Frames

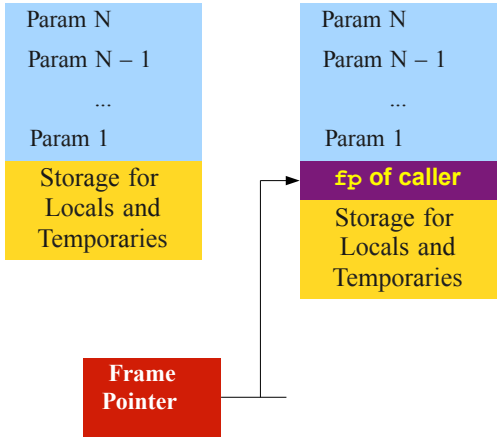


Logical vs Physical Stack Frames

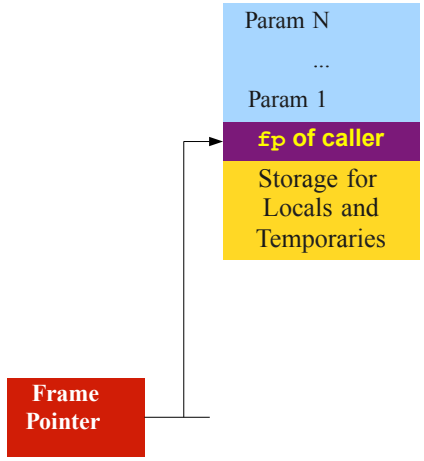




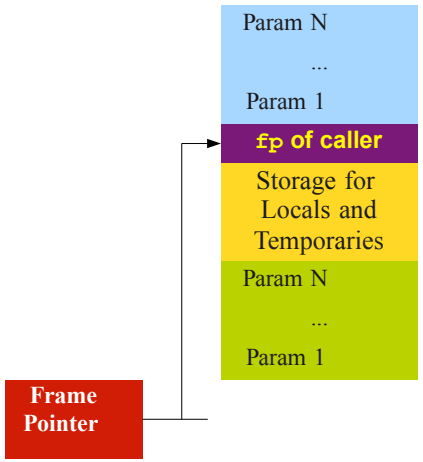
Logical vs Physical Stack Frames



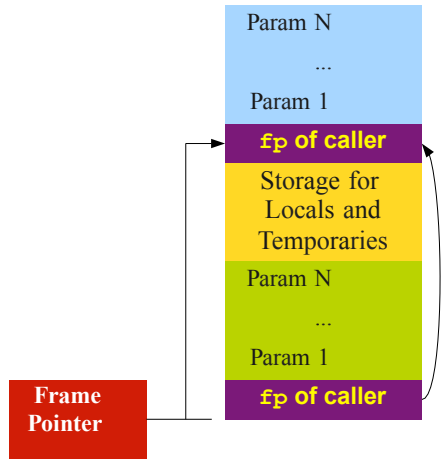
(Mostly) Physical Stack Frames



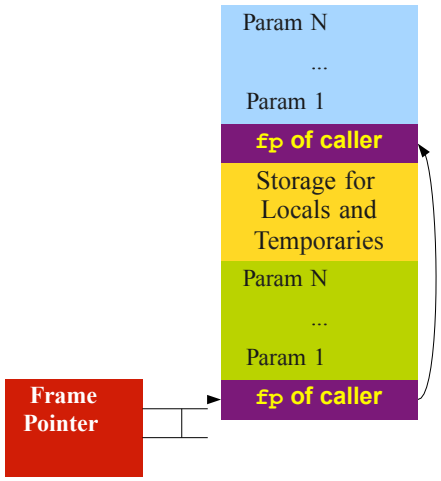
(Mostly) Physical Stack Frames



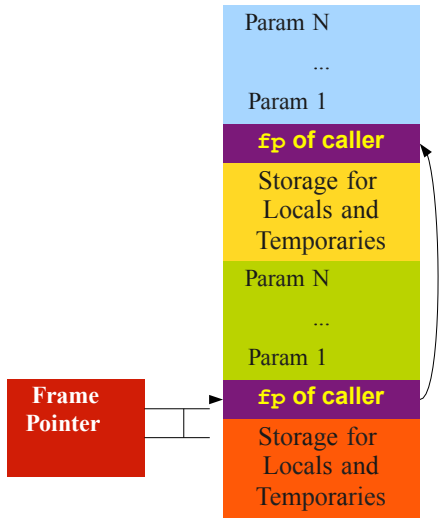
(Mostly) Physical Stack Frames



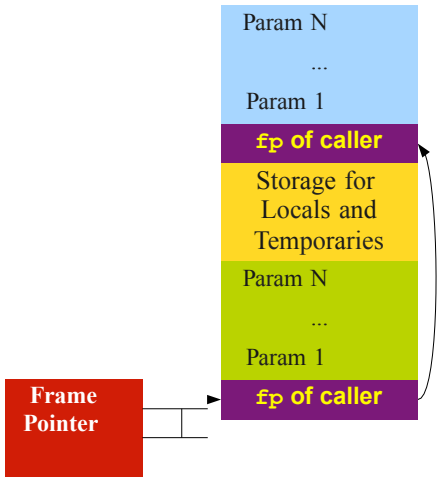
(Mostly) Physical Stack Frames



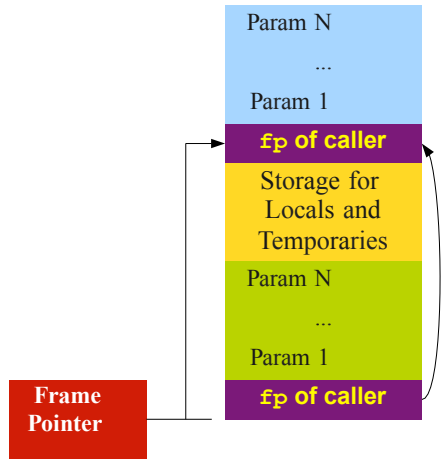
(Mostly) Physical Stack Frames



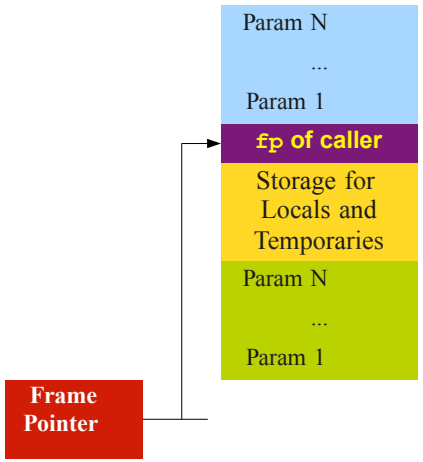
(Mostly) Physical Stack Frames



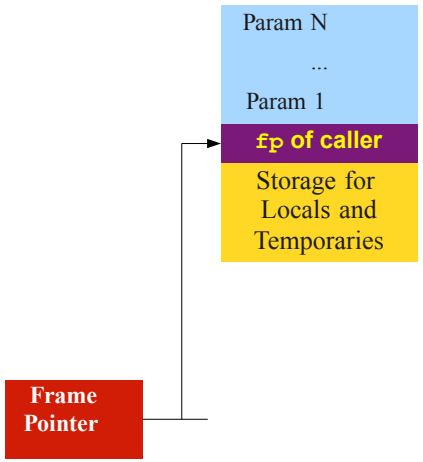
(Mostly) Physical Stack Frames



(Mostly) Physical Stack Frames



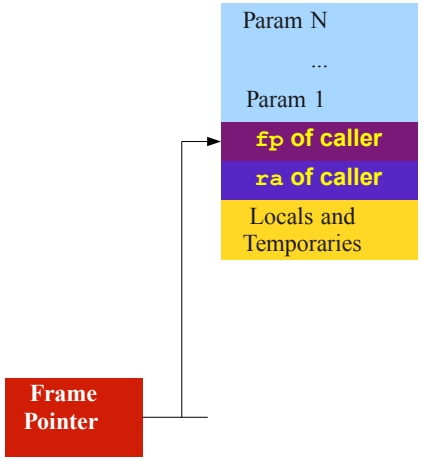
(Mostly) Physical Stack Frames



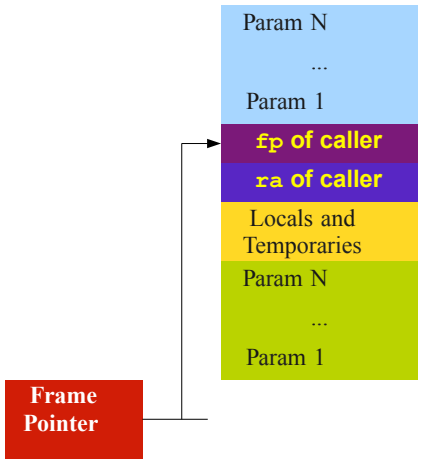
The Stored Return Address

- Internally, the processor has a special register called the **program counter** (PC) that stores the address of the next instruction to execute.
- Whenever a function returns, it needs to restore the PC so that the calling function resumes execution where it left off.
- The address of where to return is stored in MIPS in a special register called **`ra`** ("return address.")
- To allow MIPS functions to call one another, each function needs to store the previous value of **`ra`** somewhere.

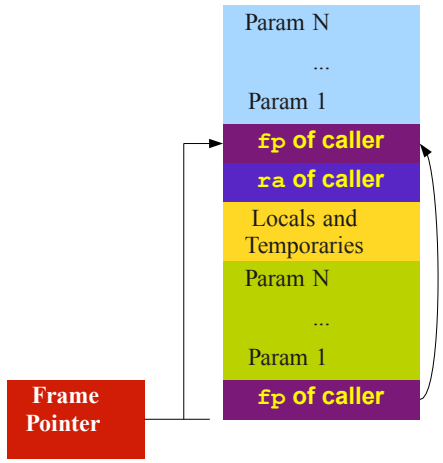
Physical Stack Frames



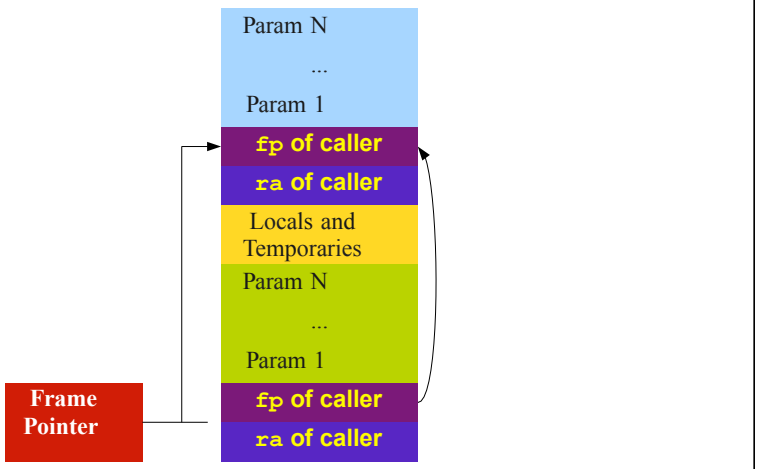
Physical Stack Frames



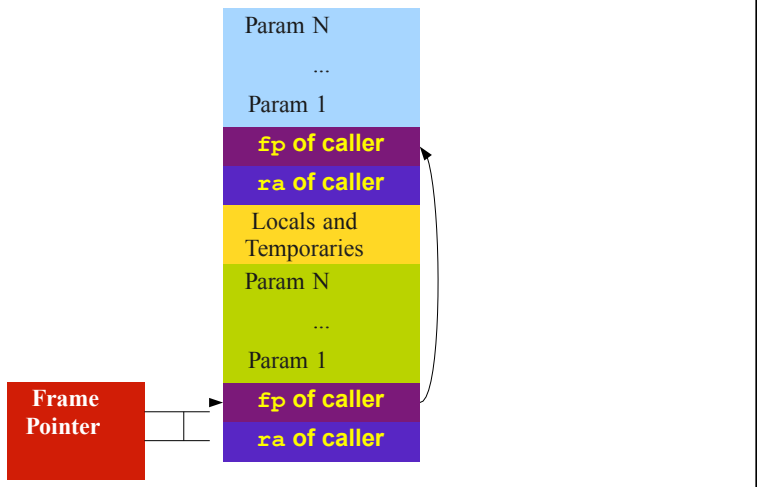
Physical Stack Frames



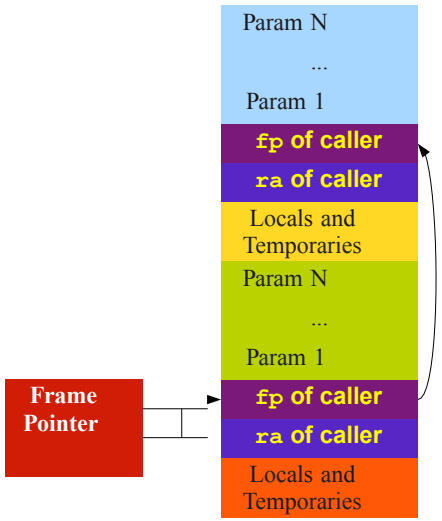
Physical Stack Frames



Physical Stack Frames

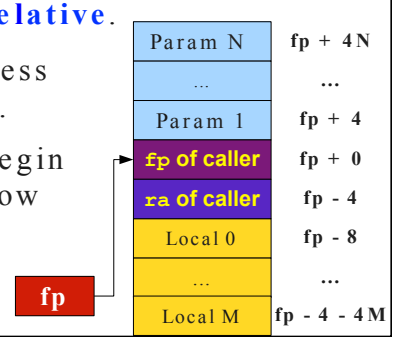


Physical Stack Frames



So What?

- In your code generator, you must assign each local variable, parameter, and temporary variable its own location.
- These locations occur in a particular stack frame and are called **fp-relative**.
- Parameters begin at address **`fp + 4`** and grow upward.
- Locals and temporaries begin at address **`fp − 8`** and grow downward



From Your Perspective

```
Location* location =
    new Location(fpRelative, +4, locName);
```

From Your Perspective

```
Location* location =
    new Location(fpRelative, +4, locName);
```

From Your Perspective

```
Location* location =
    new Location(fpRelative, +4, locName);
```

What variable does this refer to?

And One More Thing…

```
int globalVariable;

int main() {
    globalVariable = 137;
}
```

And One More Thing…

```
int globalVariable;

int main() {
    globalVariable = 137;
}
```

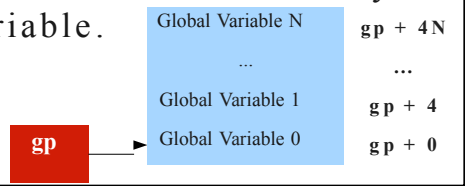
And One More Thing…

```
int globalVariable;

int main() {
    globalVariable = 137;
}
```

Where is this stored?

The Global Pointer

- MIPS also has a register called the **global pointer** (**gp**) that points to globally accessible storage.
- Memory pointed at by the global pointer is treated as an array of values that grows upward.
- You must choose an offset into this array for each global variable.



From Your Perspective

```
Location* global =
    new Location(gpRelative, +8, locName);
```

From Your Perspective

```
Location* global =
    new Location(gpRelative, +8, locName);
```

Generating TAC

TAC Generation

- At this stage in compilation, we have
  - an AST,
  - annotated with scope information,
  - and annotated with type information.
- To generate TAC for the program, we do (yet another) recursive tree traversal!
  - Generate TAC for any subexpressions or substatements.
  - Using the result, generate TAC for the overall expression.

TAC Generation for Expressions

- Define a function **`cgen`**(*expr*) that generates TAC that computes an expression, stores it in a temporary variable, then hands back the name of that temporary.
- Define **`cgen`** directly for atomic expressions (constants, **`this`**, identifiers, etc.).
- Define **`cgen`** recursively for compound expressions (binary operators, function calls, etc.)

cgen for Basic Expressions

cgen(*k*) = { // *k* is a constant
    Choose a new temporary *t*
    Emit(*t* = *k*);
    Return *t*
}
cgen(*id*) = { // *id* is an identifier
    Choose a new temporary *t*
    Emit(*t* = *id*)
    Return *t*
}

cgen for Binary Operators

cgen(e_1 + e_2) = {
    Choose a new temporary *t*
    Let t_1 = **cgen**(e_1)
    Let t_2 = **cgen**(e_2)
    Emit(*t* = t_1 + t_2)
    Return *t*
}

An Example

cgen(5 + x) = {
  Choose a new temporary *t*
  Let t_1 = **cgen**(5)
  Let t_2 = **cgen**(x)
  Emit ($t = t_1 + t_2$)
  Return t
}

An Example

cgen(5 + x) = {
  Choose a new temporary *t*
  Let t_1 = {
    Choose a new temporary *t*
    Emit(*t* = 5)
    return *t*
  }
  Let t_2 = {
    Choose a new temporary *t*
    Emit(*t* = x)
    return *t*
  }
  Emit ($t = t_1 + t_2$)
  Return t
}

```
_t0 = 5
_t1 = x
_t2 = _t0 + _t1
```

cgen for Statements

- We can extend the **cgen** function to operate over statements as well.
- Unlike **cgen** for expressions, **cgen** for statements does not return the name of a temporary holding a value.
  - *(Why?)*

cgen for Simple Statements

cgen(*expr*;) = {
    cgen(*expr*)
}

cgen for **while** loops

cgen(**while** (*expr*) *stmt*) =
{ Let L_{before} be a new label.
Let L_{after} be a new label.
Emit(L_{before} **:**)
Let *t* = **cgen**(*expr*)
Emit(**IfZ** *t* **Goto** L_{after})
cgen(*stmt*)
Emit(**Goto** L_{before})
Emit(L_{after} **:**)
}