Imperative Programming
The Case of FORTRAN

ICOM 4036

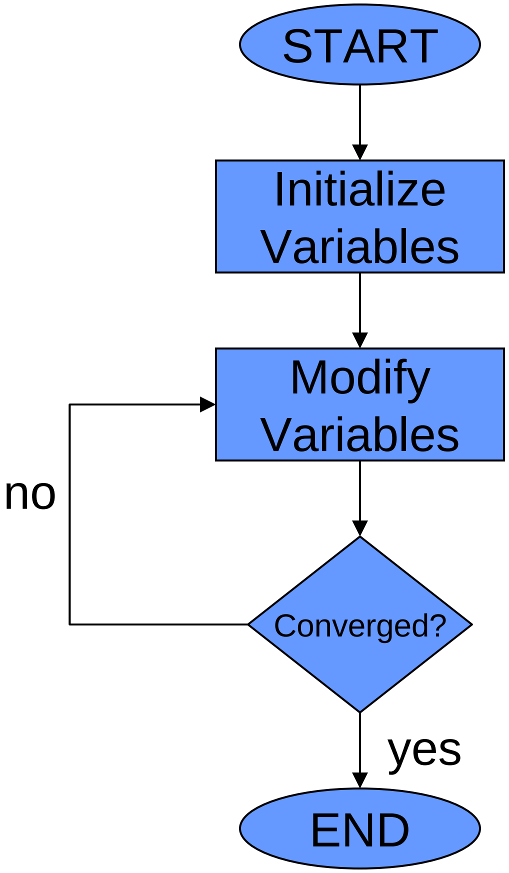
Lecture 5

The Imperative Paradigm

- Computer Model consists of bunch of variables
- A program is a sequence of state modifications or <u>assignment statements</u> that converge to an answer
- PL provides multiple tools for structuring and organizing these steps
  - E.g. Loops, procedures

This is what you have been doing since INGE 3016!

A Generic Imperative Program



Imperative Fibonacci Numbers (C)

```
int fibonacci(int f0, int f1, int n) {
    // Returns the nth element of the Fibonacci sequence
    int fn = f0;
    for (int i=0; i<n; i++) {
        fn = f0 + f1;
        f0 = f1;
        f1 = fn;
    }
    return fn;
}
```

Examples of (Important) Imperative Languages

- FORTRAN (J. Backus IBM late 50’s)
- Pascal (N. Wirth 70’s)
- C (Kernigham & Ritchie AT&T late 70’s)
- C++ (Stroustrup AT&T 80’s)
- Java (Sun Microsystems late 90’s)
- C# (Microsoft 00’s)

FORTRAN Highlights

- For High Level Programming Language ever implemented
- First compiler developed by IBM for the IBM 704 computer
- Project Leader: John Backus
- Technology-driven design
  - Batch processing, punched cards, small memory, simple I/O, GUI’s not invented yet

Some Online References

- Professional Programmer’s Guide to FORTRAN
- Getting Started with G77

Links available on course web site

Structure of a FORTRAN program

```
PROGRAM <name>

   <program_body>

END

SUBROUTINE <name> (args)

   <subroutine_body>

END

FUNCTION <name> (args)

   <function_body>

END
…
```

Lexical/Syntactic Structure

- One statement per line
- First 6 columns reserved
- Identifiers no longer than 6 symbols
- Flow control uses numeric labels
- Unstructured programs possible

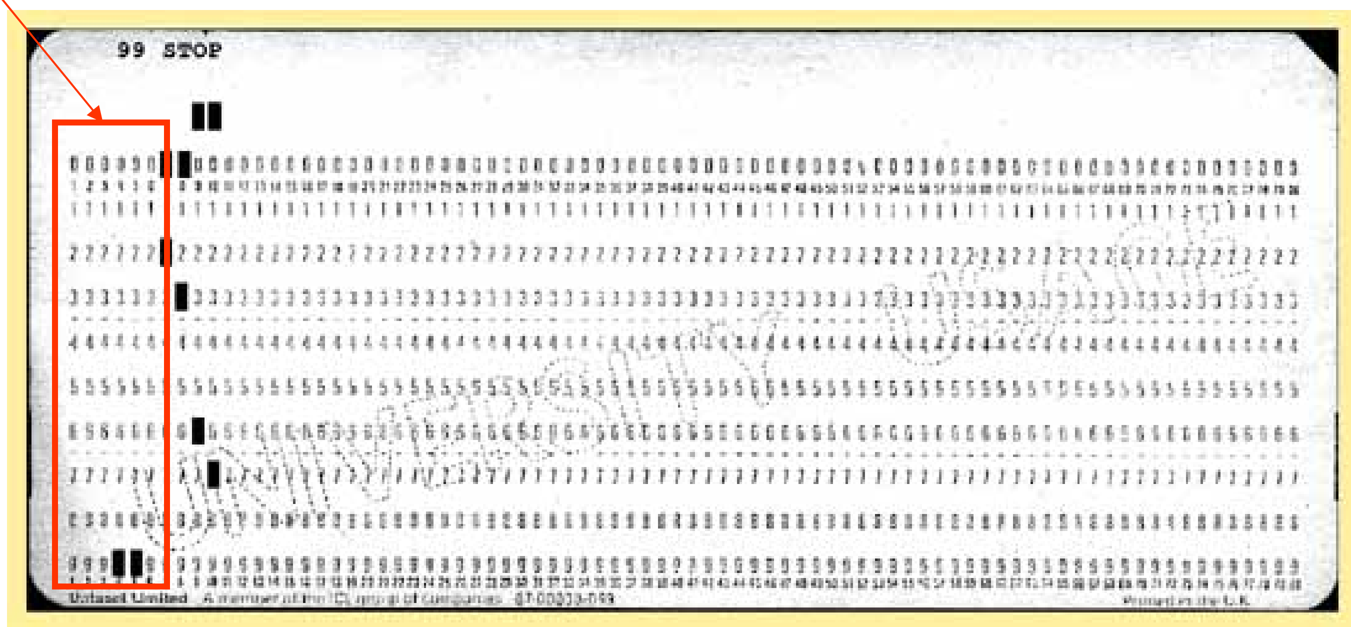
Hello World in Fortran

```
      PROGRAM TINY
          WRITE(UNIT=*, FMT=*) 'Hello, world'
      END
```

One Statement Per line

First 6 columns Reserved

Designed with the Punched Card in Mind



FORTRAN By Example 2

```
      PROGRAM LOAN
        WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
        READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
        RATE = PCRATE / 100.0
        REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
        WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      END
```

Implicitly Defined Variables
Type determined by initial letter
I-M ~ INTEGER
A-H, O-Z FLOAT

FORTRAN By Example 2

```
      PROGRAM LOAN
        WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
        READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
        RATE = PCRATE / 100.0
        REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
        WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      END
```

FORTRAN's Version
of
Standard Output Device

FORTRAN By Example 2

```
      PROGRAM LOAN
        WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
        READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
        RATE = PCRATE / 100.0
        REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
        WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      END
```

FORTRAN’s Version
of
Default Format

FORTRAN By Example 3

```
      PROGRAM REDUCE
      WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
      READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
      RATE = PCRATE / 100.0
      REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
      WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      WRITE(UNIT=*, FMT=*)'End of Year Balance'
      DO 15,IYEAR = 1,NYEARS,1
          AMOUNT = AMOUNT + (AMOUNT * RATE) - REPAY
          WRITE(UNIT=*, FMT=*)IYEAR, AMOUNT
   15 CONTINUE
      END
```

A loop consists of two separate statements
-> Easy to construct **unstructured** programs

FORTRAN Do Loops

```
      PROGRAM REDUCE
      WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
      READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
      RATE = PCRATE / 100.0
      REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
      WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      WRITE(UNIT=*, FMT=*)'End of Year Balance'
      DO 15,IYEAR = 1,NYEARS,1
          AMOUNT = AMOUNT + (AMOUNT * RATE) - REPAY
          WRITE(UNIT=*, FMT=*)IYEAR, AMOUNT
   15 CONTINUE
      END
```

```
Enter amount, % rate, years
2000, 9.5, 5
Annual repayments are 520.8728
End of Year Balance
       1 1669.127
       2 1306.822
       3 910.0968
       4 475.6832
       5 2.9800416E-04
```

A loop consists of two separate statements
-> Easy to construct unstructured programs

FORTRAN Do Loops

```
      PROGRAM REDUCE
      WRITE(UNIT=*, FMT=*)'Enter amount, % rate, years'
      READ(UNIT=*, FMT=*) AMOUNT, PCRATE, NYEARS
      RATE = PCRATE / 100.0
      REPAY = RATE * AMOUNT / (1.0 - (1.0+RATE)**(-NYEARS))
      WRITE(UNIT=*, FMT=*)'Annual repayments are ', REPAY
      WRITE(UNIT=*, FMT=*)'End of Year Balance'
      DO 15,IYEAR = 1,NYEARS,1
          AMOUNT = AMOUNT + (AMOUNT * RATE) - REPAY
          WRITE(UNIT=*, FMT=*)IYEAR, AMOUNT
   15 CONTINUE
      END
```

```
Enter amount, % rate, years
2000, 9.5, 5
Annual repayments are 520.8728
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       5 2.9800416E-04
```

- optional increment (can be negative)
- final value of index variable
- index variable and initial value
- end label

FORTRAN Functions

```
      PROGRAM TRIANG
        WRITE(UNIT=*,FMT=*)'Enter lengths of three sides:'
        READ(UNIT=*,FMT=*) SIDEA, SIDEB, SIDEC
        WRITE(UNIT=*,FMT=*)'Area is ', AREA3(SIDEA,SIDEB,SIDEC)
      END

      FUNCTION AREA3(A, B, C)
*     Computes the area of a triangle from lengths of sides
        S = (A + B + C)/2.0
        AREA3 = SQRT(S * (S-A) * (S-B) * (S-C))
      END
```

- No recursion
- Parameters passed by reference only
- Arrays allowed as parameters
- No nested procedure definitions – Only two scopes
- Procedural arguments allowed
- No procedural return values

Think: why do you think FORTRAN designers made each of these choices?

FORTRAN IF-THEN-ELSE

```
      REAL FUNCTION AREA3(A, B, C)
*       Computes the area of a triangle from lengths of its sides.
*       If arguments are invalid issues error message and returns
*       zero.
        REAL A, B, C
        S = (A + B + C)/2.0
        FACTOR = S * (S-A) * (S-B) * (S-C)
        IF(FACTOR .LE. 0.0) THEN
          STOP 'Impossible triangle'
        ELSE
          AREA3 = SQRT(FACTOR)
        END IF
      END
```

NO RECURSION ALLOWED IN FORTRAN77 !!!

FORTRAN ARRAYS

```
   SUBROUTINE MEANSD(X, NPTS, AVG, SD)
     INTEGER NPTS
     REAL X(NPTS), AVG, SD
     SUM = 0.0
     SUMSQ = 0.0
     DO 15, I = 1,NPTS
       SUM = SUM + X(I)
       SUMSQ = SUMSQ + X(I)**2
15   CONTINUE
     AVG = SUM / NPTS
     SD = SQRT(SUMSQ - NPTS * AVG)/(NPTS-1)
   END
```

Subroutines are analogous to void functions in C

Parameters are passed by <u>reference</u>

```
 subroutine checksum(buffer,length,sum32)

C       Calculate a 32-bit 1's complement checksum of the input buffer, adding
C       it to the value of sum32.  This algorithm assumes that the buffer
C       length is a multiple of 4 bytes.

C       a double precision value (which has at least 48 bits of precision)
C       is used to accumulate the checksum because standard Fortran does not
C       support an unsigned integer datatype.

C       buffer  - integer buffer to be summed
C       length  - number of bytes in the buffer (must be multiple of 4)
C       sum32   - double precision checksum value (The calculated checksum
C                 is added to the input value of sum32 to produce the
C                 output value of sum32)

      integer buffer(*),length,i,hibits
      double precision sum32,word32
      parameter (word32=4.294967296D+09)
C                 (word32 is equal to 2**32)

C       LENGTH must be less than 2**15, otherwise precision may be lost
C       in the sum
      if (length .gt. 32768)then
         print *, 'Error: size of block to sum is too large'
         return
      end if

      do i=1,length/4
         if (buffer(i) .ge. 0)then
            sum32=sum32+buffer(i)
         else
C              sign bit is set, so add the equivalent unsigned value
            sum32=sum32+(word32+buffer(i))
         end if
      end do

C       fold any overflow bits beyond 32 back into the word
10      hibits=sum32/word32
      if (hibits .gt. 0)then
         sum32=sum32-(hibits*word32)+hibits
         go to 10
      end if

      end
```

WhiteBoard Exercises

- Computing machine precision
- Computing the integral of a function
- Solving a linear system of equations

FORTRAN Heavily used in scientific computing applications

Implementing Procedures

- Why procedures?
  - Abstraction
  - Modularity
  - Code re-use
- Initial Goal
  - Write segments of assembly code that can be re-used, or “called” from different points in the main program.
  - KISS: Keep It Simple Stupid:
    - no parameters, no recursion, no locals, no return values

Procedure Linkage Approach I

- Problem
  - procedure must determine where to return after servicing the call
- Solution: Architecture Support
  - Add a jump instruction that saves the return address in some place known to callee
    - MIPS: jal instruction saves return address in register $ra
  - Add an instruction that can jump to return address
    - MIPS: jr instruction jumps to the address contained in its argument register

Computing Integer Division (Procedure Version)

Iterative C++ Version

```
int a = 0;
int b = 0;
int res = 0;
main () {
  a = 12;
  b = 5;
  res = 0;
  div();
  printf(“Re
}
void div(voi
  while (a >
    a = a -
    res ++;
  }
}
```

C+

MIPS
Assembly Language

```
            .data
x:          .word   0
y:          .word   0
res:        .word   0
pf1:        .asciiz "Result = "
pf2:        .asciiz "Remainder = "
            .globl      main
            .text
main:                                           # int main() {
                                                #   //      ssumes registers sx unused

            la          $s0, x
            li          $s1, 12
            sw          $s1, 0($s0)
            la          $s0, y
            li          $s2, 5
            sw          $s2, 0($s0)
            la          $s0, res                #   res = 0;
            li          $s3, 0
            sw          $s3, 0($s0)
            jal         d                       #   div();
            lw          $s3, 0($s0)
            la          $a0, pf1                #   printf("Result = %d \n");
            li          $v0, 4                  #   //system call to print_str
            syscall
            move        $a0, $s3
            li          $v0, 1                  #   //system call to print_int
            syscall
            la          $a0, pf2                #   printf("Remainder = %d \n");
            li          $v0, 4                  #   //system call to print_str
            syscall
            move        $a0, $s1
            li          $v0, 1                  #   //system call to print_int
            syscall
            jr          $ra                     #   return // TO Operating System
```

Function Call

Computing Integer Division (Procedure Version)

Iterative C++ Version

```
int a = 0;
int b = 0;
int res = 0;
main () {
  a = 12;
  b = 5;
  res = 0;
  div();
  printf(“Res = %
}
void div(void) {
  while (a >= b) {
    a = a - b;
    res ++;
  }
}
```

C++

```
# div function
# PROBLEM: Must save args and registers before using them
d:                                              # void d(void) {
                                                #   // Allocate registers for globals
            la          $s0, x                  #   // x in $s1
            lw          $s1, 0($s0)
            la          $s0, y                  #   // y in $s2
            lw          $s2, 0($s0)
            la          $s0, res                #   // res in $s3
            lw          $s3, 0($s0)
while:      bgt         $s2, $s1, ewhile        #   while (x <= y) {
            sub         $s1, $s1, $s2           #     x = x - y
            addi        $s3, $s3, 1             #     res ++
            j           while                   #   }
ewhile:                                         #   // Update variables in memory
            la          $s0, x
            sw          $s1, 0($s0)
            la          $s0, y
            sw          $s2, 0($s0)
            la          $s0, res
            sw          $s3, 0($s0)
enddiv:     jr          $ra                     #   return;
                                                # }
```

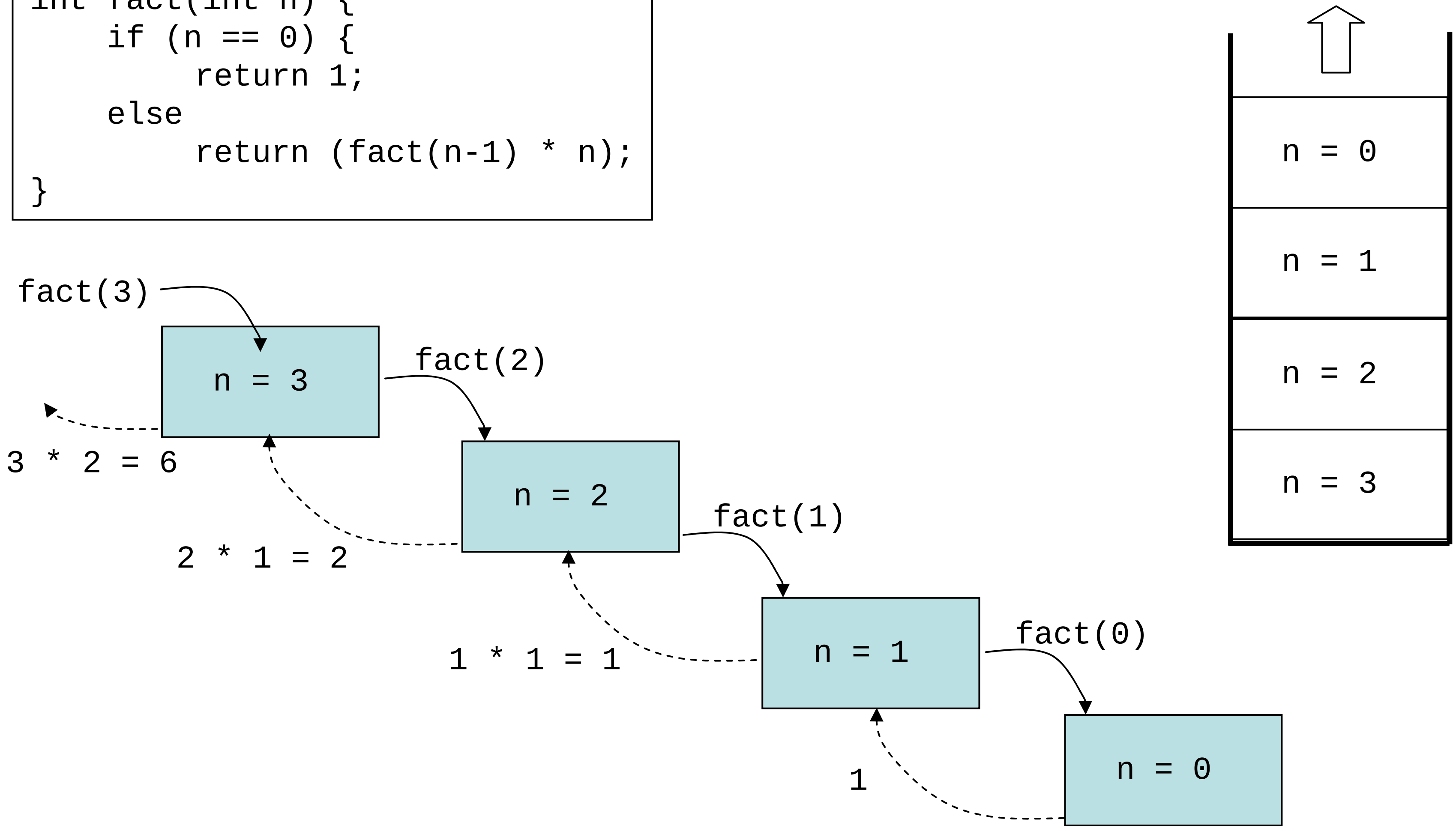
MIPS
Assembly Language

Pending Problems With Linkage Approach I

- Registers shared by all procedures
  - procedures must save/restore registers (use stack)
- Procedures should be able to call other procedures
  - save multiple return addresses (use stack)
- Lack of parameters forces access to globals
  - pass parameters in registers
- Recursion requires multiple copies of local data
  - store multiple procedure activation records (use stack)
- Need a convention for returning function

Recursion Basics

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



fact(3)

n = 3

fact(2)

3 * 2 = 6

n = 2

2 * 1 = 2

fact(1)

n = 1

1 * 1 = 1

fact(0)

n = 0

1

n = 0

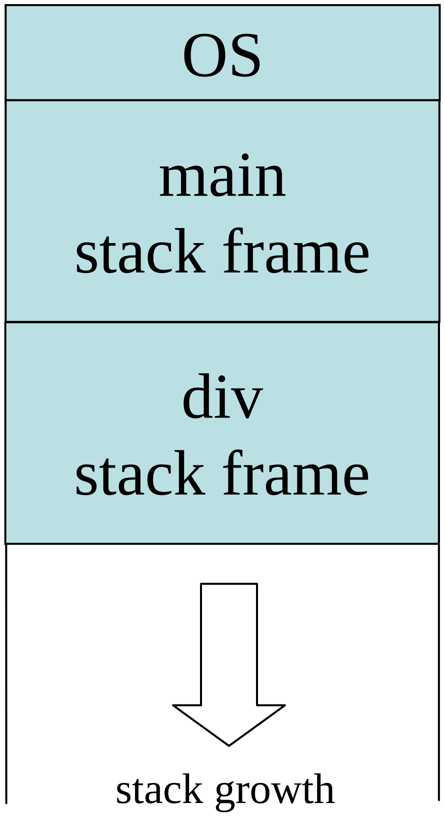
n = 1

n = 2

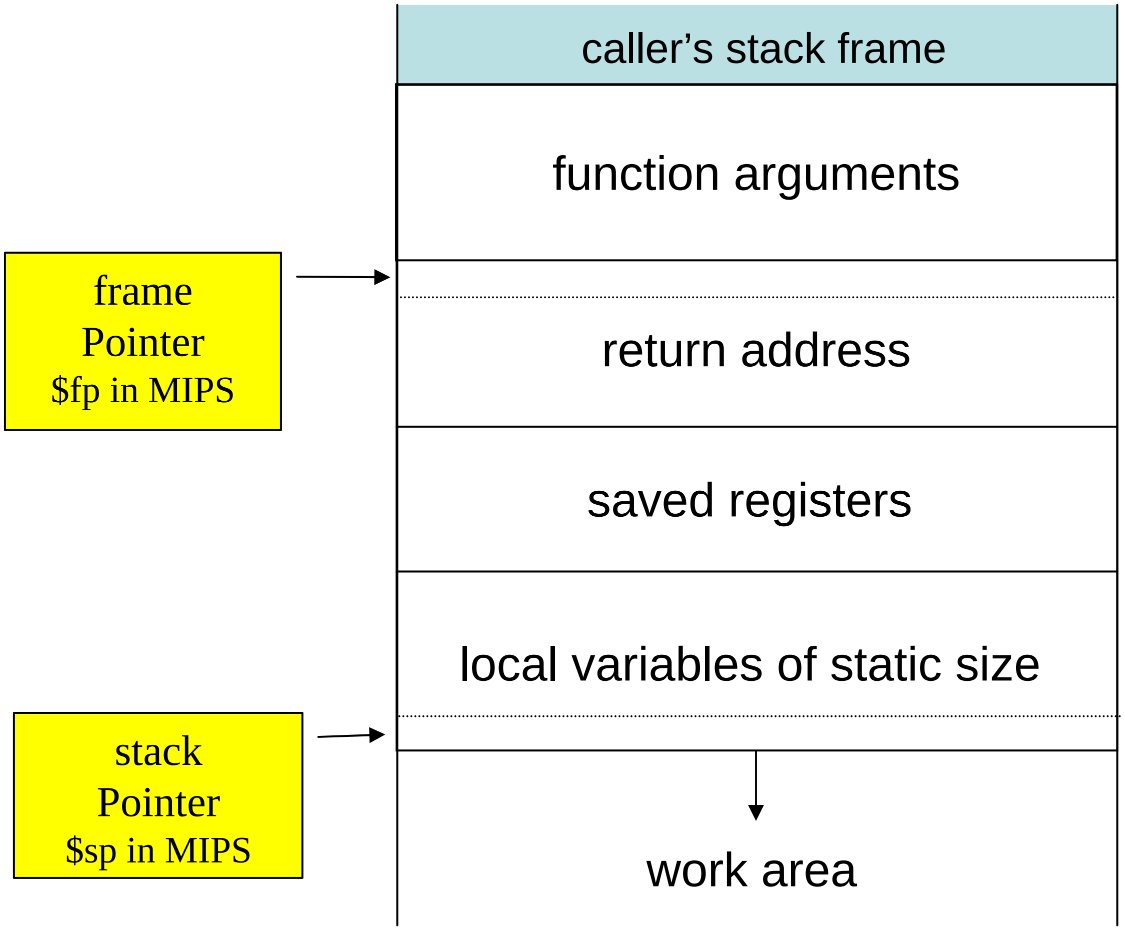
n = 3

Solution: Use Stacks of Procedure Frames

- Stack frame contains:
  - Saved arguments
  - Saved registers
  - Return address
  - Local variables



Anatomy of a Stack Frame



caller’s stack frame

function arguments

frame Pointer $fp in MIPS

return address

saved registers

local variables of static size

stack Pointer $sp in MIPS

work area

Contract: Every function must leave the stack the way it found it

Example: Function Linkage using Stack Frames

```
int x = 0;
int y = 0;
int res = 0;
main () {
  x = 12;
  y = 5;
  res = div(x,y);
  printf(“Res = %d”,res);
}
int div(int a,int b) {
  int res = 0;
  if (a >= b) {
    res = div(a-b,b) + 1;
  }
  else {
    res = 0;
  }
  return res;
}
```

- Add return values
- Add parameters
- Add recursion
- Add local variables

Example: Function Linkage using Stack Frames

```
div:        sub         $sp, $sp, 28            # Alloc space for 28 byte stack frame
            sw          $a0, 24($sp)            # Save argument registers
            sw          $a1, 20($sp)            # a in $a0
            sw          $ra, 16($sp)            # Save other registers as needed
            sw          $s1, 12($sp)            # Save callee saved registers ($sx)
            sw          $s2, 8($sp)
            sw          $s3, 4($sp)             # No need to save $s4, since not used
            li          $s3, 0
            sw          $s3, 0($sp)             # int res = 0;
                                                # Allocate registers for locals
            lw          $s1, 24($sp)            #   a in $s1
            lw          $s2, 20($sp)            #   b in $s2
            lw          $s3, 0($sp)             #   res in $s3

if:         bgt         $s2, $s1, else          # if (a >= b) {
            sub         $a0, $s1, $s2           #
            move        $a1, $s2
            jal         div                     #
            addi        $s3, $v0, 1             #   res = div(a-b, b) + 1;
            j           endif                   # }
else:       li          $s3, 0                  # else { res = 0; }
endif:
            sw          $s1, 32($sp)            #   deallocate a from $s1
            sw          $s2, 28($sp)            #   deallocate b from $s2
            sw          $s3, 0($sp)             #   deallocate res from $s3
            move        $v0, $s3                # return res

            lw          $a0, 24($sp)            # Restore saved registers
            lw          $a1, 20($sp)            # a in $a0
            lw          $ra, 16($sp)            # Save other registers as needed
            lw          $s1, 12($sp)            # Save callee saved registers ($sx)
            lw          $s2, 8($sp)
            lw          $s3, 4($sp)             # No need to save $s4, since not used
            addu        $sp, $sp, 28            # pop stack frame
enddiv:     jr          $ra                     # return;
#
```

MIPS: Procedure Linkage Summary

- First 4 arguments passed in $a0-$a3
- Other arguments passed on the stack
- Return address passed in $ra
- Return value(s) returned in $v0-$v1
- Sx registers saved by callee
- Tx registers saved by caller