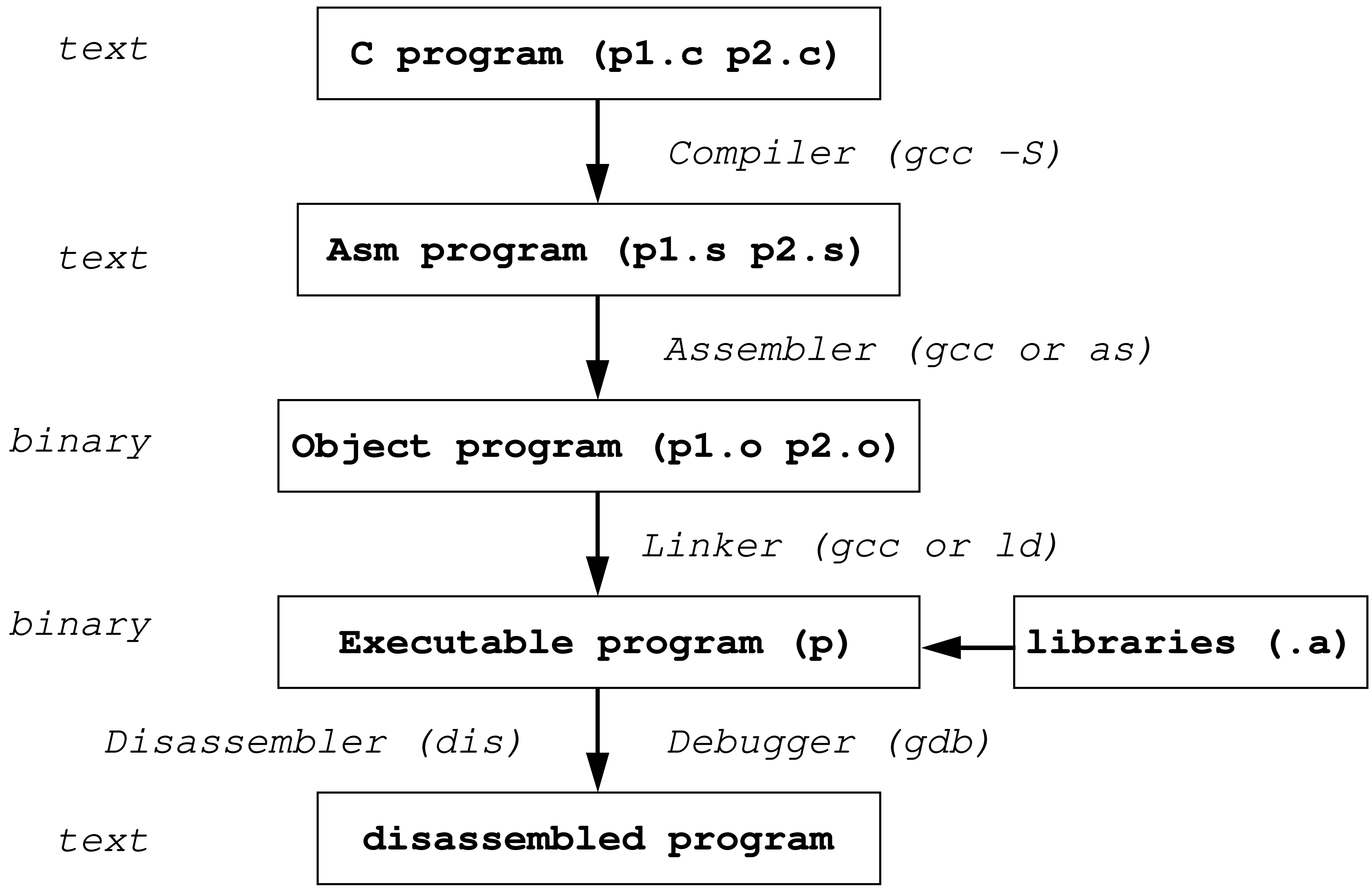
MIPS Programming
CS 740

Sept. 19, 1996

Topics

- Basics
- Control Flow
- Procedures
- Data Representations
- Instruction Formats

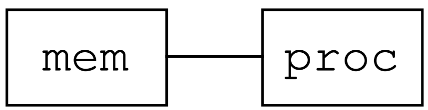
Translation Process



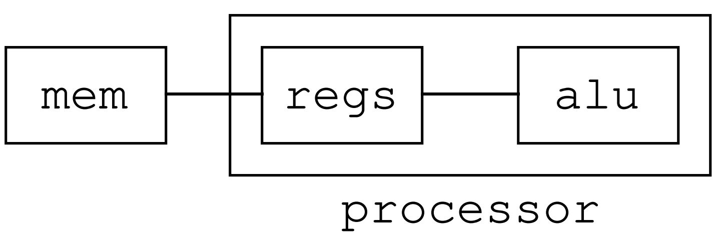
Abstract machines

Machine Model	Data	Control
C	1) char 2) int, float 3) double 4) struct, array 5) pointer	1) loops 2) conditionals 3) goto
ASM	1) byte 2) word 3) doubleword 4) contiguous word allocation 5) address of initial byte	3) branch

C



ASM



MIPS Register Convention

General Purpose Registers

- 32 total
- Store integers and pointers
- Fast access: 2 reads, 1 write in single cycle

Usage Conventions

- Established as part of architecture
- Used by all compilers, programs, and libraries
- Assures object code compatibility
  - E.g., can mix Fortran and C

Register	Name	Usage
$0	$0	Constant 0
$1	$at	Reserved Temp.
$2	$v0	Return Values
$3	$v1	
$4	$a0	Procedure arguments
$5	$a1	
$6	$a2	
$7	$a3	
$8	$t0	Caller Save Temporaries: May be overwritten by called procedures
$9	$t1	
$10	$t2	
$11	$t3	
$12	$t4	
$13	$t5	
$14	$t6	
$15	$t7	

Registers (cont.)

Important Ones for Now

$0	Constant 0
$2	Return Value
$3	Can use as temporary
$4	First argument
$5	Second argument
$31	Return address

Register	Name	Use
$16	$s0	Callee Save Temporaries: May not be overwritten by called procedures
$17	$s1	
$18	$s2	
$19	$s3	
$20	$s4	
$21	$s5	
$22	$s6	
$23	$s7	
$24	$t8	Caller Save Temp
$25	$t9	
$26	$k0	Reserved for Operating Sys
$27	$k1	
$28	$gp	Global Pointer
$29	$sp	Stack Pointer
$30	$s8	Callee Save Temp
$31	$ra	Return Address

Program Representations

C Code

```
int gval;

void test1(int x, int y)
{
  gval = (x+x+x) - (y+y+y);
}
```

Obtain with command

`gcc -O -S code.c`

Produces file `code.s`

Compiled to Assembly

```
        .comm   gval,8

        .loc    1 7
        .ent    test1
test1:
        .frame  $sp,0,$31
        .mask   0x00000000,0
        .fmask  0x00000000,0
        addu    $3,$4,$4
        addu    $3,$3,$4
        addu    $2,$5,$5
        addu    $2,$2,$5
        subu    $3,$3,$2
        sw      $3,gval
        j       $31
        .end    test1
```

Prog. Representation (Cont.)

Object

```
0x400230 <test1>:
    0x00841821
    0x00a51021
    0x00451021
    0x00641821
    0x00621823
    0x03e00008
    0xaf838108
```

Disassembled

```
0x400230 <test1>:        addu $v1,$a0,$a0
0x400234 <test1+4>:      addu $v0,$a1,$a1
0x400238 <test1+8>:      addu $v0,$v0,$a1
0x40023c <test1+12>:     addu $v1,$v1,$a0
0x400240 <test1+16>:     subu $v1,$v1,$v0
0x400244 <test1+20>:     jr $ra
0x400248 <test1+24>:     sw $v1,-32504($gp)
```

Run gdb on object code

```
x/7 0x400230

dissassemble test1
```

Delayed Branches

C Code

```c
int test2(int x, int y)
{
  return (x+x+x) - (y+y+y);
}
```

Compiled to Assembly

```
        .loc    1 12
        .ent    test2
test2:
        .frame  $sp,0,$31
        .mask   0x00000000,0
        .fmask  0x00000000,0
        addu    $2,$4,$4
        addu    $2,$2,$4
        addu    $3,$5,$5
        addu    $3,$3,$5
        .set    noreorder
        .set    nomacro
        j       $31
        subu    $2,$2,$3
        .set    macro
        .set    reorder

        .end    test2
```

Annotated Delayed Branch Code

C Code

```
int test2(int x, int y)
{
  return (x+x+x) - (y+y+y);
}
```

Annotated Assembly

```
test2:
        # x in $4, y in $5
        # Return result in $2
        addu    $2,$4,$4   # $2 = x+x
        addu    $2,$2,$4   # $2 += x
        addu    $3,$5,$5   # $3 = y+y
        addu    $3,$3,$5   # $3 += y
        J       $31        # (Delayed) return
        subu    $2,$2,$3   # with value $2-$3
```

Notation Convention

- Upper case denotes delayed branch
- Lower case denotes normal branch

For Exposition Only

- Actual machine supports only delayed branches
- Regular ones converted by assembler

Pointer Examples

C Code

```
int iaddp(int *xp, int *yp)
{
  int x = *xp;
  int y = *yp;
  return x + y;
}
```

```
void incr(int *sum, int v)
{
  int old = *sum;
  int new = old+val;
  *sum = new;
}
```

Annotated Assembly

```
iaddp:
        lw      $2,0($4)   # $2 = *xp
        lw      $3,0($5)   # $3 = *yp
        J       $31        # (delayed) return
        addu    $2,$2,$3   # with value $2+$3
```

```
incr:
        lw      $2,0($4)   # $2 = *sum
        #nop
        addu    $2,$2,$5   # $2+= v
        J       $31        # (delayed) return
        sw      $2,0($4)   # with *sum = $2
```

Array Indexing

C Code

```
int aref(int a[], int i)
{
  return a[i];
}
```

```
int garray[10];

int gref(int i)
{
  return garray[i];
}
```

Annotated Assembly

```
aref:
        sll     $5,$5,2  # $5 = 4*i
        addu    $5,$5,$4 # $5 = &a[i]
        lw      $2,0($5) # return val. = a[i]
        j       $31      # Return
```

```
        .comm   garray,40

gref:
    sll $4,$4,2        # $4 = 4*i
    lw  $2,garray($4)  #Return val = garray[i]
    j   $31            # Return
```

Disassembled:

```
0x40034c <gref>:        sll $a0,$a0,0x2
0x400350 <gref+4>:      lui $v0,4096
0x400354 <gref+8>:      addu $v0,$v0,$a0
0x400358 <gref+12>:     lw $v0,4304($v0)
0x40035c <gref+16>:     JR $ra
0x400360 <gref+20>:     nop
```

Structures & Pointers

C Code

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

i	a	p
0	4	16

```
void addr(struct rec *r)
{
  int *loc;
  r->i = 1;
  loc = &r->a[r->i];
  r->p = loc;
  *(r->p) = 2;
  r->a[0] = 4;
  *(r->p+1) = 8;
}
```

Annotated Assembly

```
addr:
        li      $2,0x00000001 # $2 = 1
        sw      $2,0($4)      # r->i = 1
        addu    $2,$4,8       # $2 = &r->a[1]
        sw      $2,16($4)     # r->p = $2
        li      $2,0x00000002 # $2 = 1
        sw      $2,8($4)      # r->a[1] = 2
        lw      $2,16($4)     # $2 = r->p
        li      $3,0x00000004 # $3 = 4
        li      $5,0x00000008 # $4 = 8
        sw      $3,4($4)      # r->a[0] = 4
        J       $31           # Return
        sw      $5,4($2)      # setting
                              # *(r->p+1) = 8
```

MIPS Implemented Branches

Formats

- **`bCOND Rs, Rt, label`**
  - *Cond* : Branch condition
- **`bCOND Rs, label`**
  - *Cond* : Branch condition, relative to zero

Conditions

Conditions		Reg. Arguments
`beq`	**EQual**	**2**
`bne`	**Not Equal**	**2**
`bgez`	**Greater or Equal to Zero**	**1**
`bgtz`	**Greater Than Zero**	**1**
`blez`	**Less or Equal to Zero**	**1**
`bltz`	**Less Than Zero**	**1**

Implementation

- **All have single cycle delay slot**

Branch Notation Convention

Caveat

- **For exposition only**
- **Not machine-readable assembly code**

Conventional Branches

- **Lower Case**
  - `j`, `jr`, `beq`, `bltz`, etc.
- **If branch taken, following instruction *not* executed**
- **Allowed in assembly**

Delayed Branches

- **Upper Case**
  - `J`, `JR`, `BEQ`, `BLTZ`, etc.
- **Following instruction executed whether or not branch taken**
- **Actually implemented**
- **Use assembler directives to enable/disable.**

Conditional Example

C Code

```
int max(int x, int y)
{
  return (x < y) ? y : x;
}
```

Compiled

```
max:
    # x in $4, y in $5
    slt     $2,$4,$5     # $4 < $5 ?
    beq     $2,$0,$L2    # if not, goto $L2
    move    $4,$5        # else $4 = y
$L2:
    J       $31          # Return
    move    $2,$4        # with $4
```

Disassembled

```
0x400230 <max>:         slt $v0,$a0,$a1
0x400234 <max+4>:       BEQ $v0,$zero,0x400240 <max+16>
0x400238 <max+8>:       nop
0x40023c <max+12>:      move $a0,$a1
0x400240 <max+16>:      JR $ra
0x400244 <max+20>:      move $v0,$a0
```

Loop Example

C Code

```
int fact(int x)
{
  int result = 1;
  while (x >= 2)
    result *= x--;
  return result;
}
```

Handwritten Assembly

```
fact:
        li      $2,0x1
        blt     $4,2,$L5 # Skip if x < 2
$L4:
        mul     $2,$4    # result *= x
        addi    $4,$4,-1 # x--
        bge     $4,2,$L4 # loop if x >= 2
$L5:
        j       $31      # return
        .end    fact
```

Macro-Expanded Operations

`blt $Rs, $Rt, label`

Branch if `$Rs` < `$Rt`

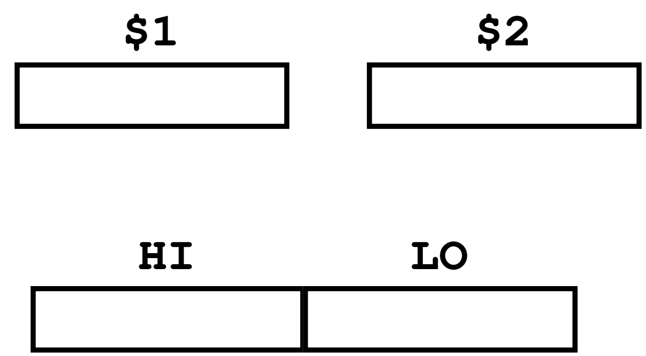
`mul $Rdest, $Rsrc`

`$Rdest *= $Rsrc`

MIPS Integer Multiplication

Multiplication Operation

- **Arguments: 32-bits each**
  - Unsigned: `multu $1, $2`
  - Signed: `mult  $1, $2`
- **Product: 64 bits**
  - Stored in special register pair
  - High & Low order words
- **Retrieve result with special instructions**
  - `mfhi $3`
  - `mflo $2`
- **SLOW!**
  - Many clock cycles



Assembled Loop Code

Handwritten Assembly

```
        li      $2,0x1
        blt     $4,2,$L5 # Skip if x < 2
$L4:
        mul     $2,$4    # result *= x
        addi    $4,$4,-1 # x--
        bge     $4,2,$L4 # loop if x >= 2
$L5:
        j       $31      # return
```

Macro expansion uses register `$1` (`$at`) as temporary

Disassembled

```
0x400ba0 <hfact>:       slti $at,$a0,2
0x400ba4 <hfact+4>:     BNE $at,$zero,0x400bc4 <hfact+36>
0x400ba8 <hfact+8>:     li $v0,1
0x400bac <hfact+12>:    multu $v0,$a0
0x400bb0 <hfact+16>:    addi $a0,$a0,-1
0x400bb4 <hfact+20>:    slti $at,$a0,2
0x400bb8 <hfact+24>:    mflo $v0
0x400bbc <hfact+28>:    BEQ $at,$zero,0x400bac <hfact+12>
0x400bc0 <hfact+32>:    nop
0x400bc4 <hfact+36>:    JR $ra
0x400bc8 <hfact+40>:    nop
```

Translation of `for` Loop

C Code

```
/* Find max ele. in array */
int amax(int a[], int count)
{
  int i;
  int result = a[0];
  for (i = 1; i < count; i++)
    if (a[i] > result)
      result = a[i];
  return result;
}
```

`for` **(*init*; *test*; *update*)**

    body

`init;`

`while`(*test*)

    { *body* ; *update* }

Annotated Assembly

```
   # *a in $4, count in $5
   # Use $6 for i, $7 for result
   lw      $7,0($4)          # result = a[0]
   li      $6,0x00000001     # i = 1
   slt     $2,$6,$5          # if !(i < count)
   beq     $2,$0,$L6         # then goto $L6
$L9:
   sll     $2,$6,2
   addu    $2,$2,$4          # $R2 = &a[i]
   lw      $3,0($2)          # $R3 = a[i]
   slt     $2,$7,$3        # if !(result < $R3)
   BEQ     $2,$0,$L7         # then goto $L7
   addu    $6,$6,1           # with count++
   move    $7,$3            # else result = $R3
$L7:
   slt     $2,$6,$5          # if i < count
   bne     $2,$0,$L9         # then goto $L9
$L6:
   J       $31               # return
   move    $2,$7             # with result
```

Compiling Switch Statements

C Code

```
typedef enum
  {ADD, MULT, MINUS, DIV, MOD, BAD}
op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
  case ADD :
    return '+';
  case MULT:
    return '*';
  case MINUS:
    return '-';
  case DIV:
    return '/';
  case MOD:
    return '%';
  case BAD:
    return '?';
  }
}
```

Implementation Options

- **Series of conditionals**
  - Good if few cases
  - Slow if many
- **Jump Table**
  - Lookup branch target
  - Avoids conditionals
  - Possible when cases are small integer constants
- **GCC**
  - Picks one based on case structure

Switch Statement Example

C Code

```
typedef enum
  {ADD, MULT, MINUS, DIV, MOD, BAD}
op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
  case ADD :
    return '+';
  case MULT:
    return '*';
  case MINUS:
    return '-';
  case DIV:
    return '/';
  case MOD:
    return '%';
  case BAD:
    return '?';
  }
}
```

Enumerated Values

```
ADD      0
MULT     1
MINUS    2
DIV      3
MOD      4
BAD      5
```

Assembly: Setup

```
  # op in $R4
li     $2,0x00000004
sltu   $2,$2,$4         #if (4 < op)
BNE    $2,$0,$L144      #then goto $L144
li     $2,0x0000003f  # with '?'
sll    $2,$4,2
lw     $2,$L143($2)     # $2 = &tab[op]
j      $2               # goto $2
```

Jump Table

Table Contents

```
$L143:
        .word   $L137
        .word   $L138
        .word   $L139
        .word   $L140
        .word   $L141
```

Enumerated Values

```
ADD      0
MULT     1
MINUS    2
DIV      3
MOD      4
BAD      5
```

Targets

```
$L137:
   J    $L144           # goto $L144
   li   $2,0x0000002b   # with '+'
$L138:
   J    $L144           # goto $L144
   li   $2,0x0000002a   # with '*'
$L139:
   J    $L144           # goto $L144
   li   $2,0x0000002d   # with '-'
$L140:
   J    $L144           # goto $L144
   li   $2,0x0000002f   # with '/'
$L141:
   li   $2,0x00000025   # $2 = '%'
```

Completion

```
$L144:
        j       $31   # return
```

Stack-Based Languages

Languages that support recursion

- E.g.: C, Pascal

Stack Allocated in *Frames*

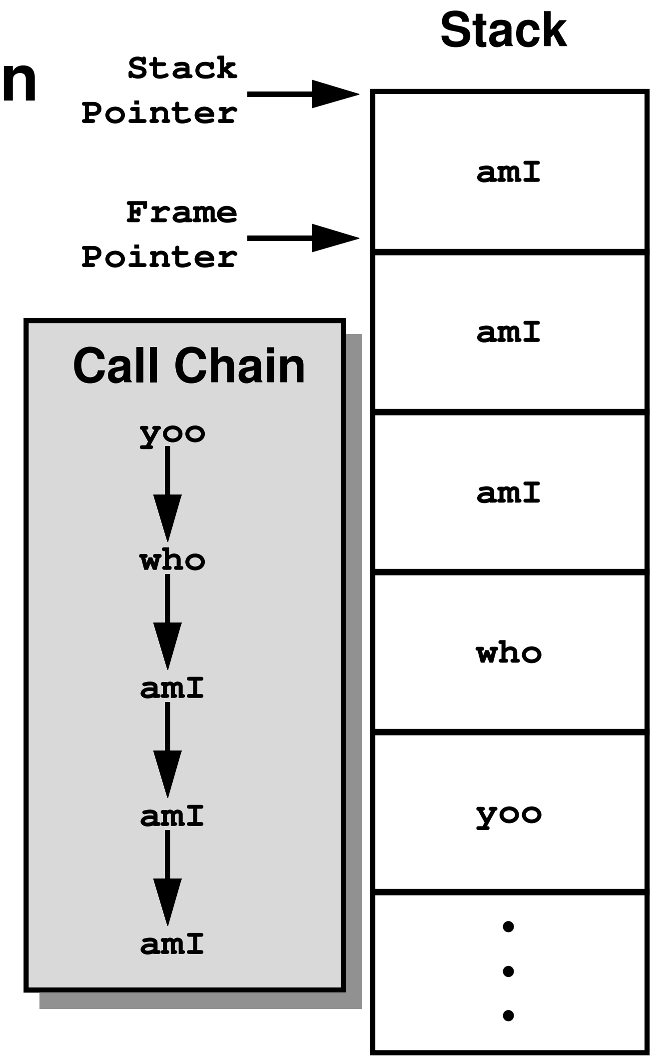
- State for procedure invocation
  - Return point, arguments, locals

Code Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

```
who(…)
{
    •
    •
    amI();
    •
    •
}
```

```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```



Saving Conventions

When procedure `yoo` calls `who`

- **`yoo` is the *caller***
- **`who` is the *callee***

Caller Save

- **If `yoo` wants value in register before & after `who` returns**
  - Save it on the stack before calling who
  - Restore after who returns

Callee Save

- **If `who` wants to use register**
  - Save current register value on stack on entry
  - Restore when returning

Saving Examples

Caller Save

- Caller must save/restore
- Callee can clobber

```
yoo:
    li $8, 17
      • • •
    sw $8, 20($sp)
    jal who
    lw $8, 20($sp)
      • • •
    mov $2, $8
    j $31
```

```
who:
    li $8, 57
      • • •
    j $31
```

Callee Save

- Callee must save/restore

```
yoo:
    li $16, 17
      • • •
    jal who
      • • •
    mov $2, $16
    j $31
```

```
who:
    sw $16, 20($sp)
    li $16, 57
      • • •
    lw $16, 20($sp)
    j $31
```

What's wrong with above code?

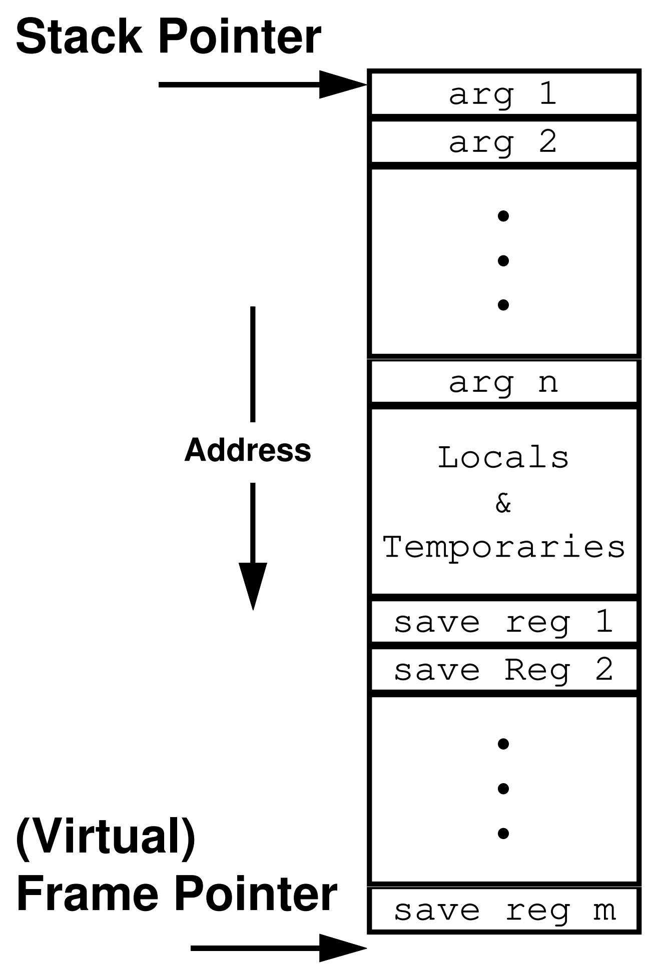
MIPS Stack Frame

Conventions

- **Agreed by all program/compiler writers**
  - Allows linking between different compilers
  - Allows symbolic debugging tools

Run Time Stack

- **Save context**
  - Registers
- **Storage for local variables**
- **Parameters to called functions**
- **Required to support recursion**



Stack Frame Requirements

Procedure Categories

- **Leaf procedures that do not use stack**
  - Do not call other procedures
  - Can fit all temporaries in caller-save registers
- **Leaf procedures that use stack**
  - Do not call other procedures
  - Need stack for temporaries
- **Non-leaf procedures**
  - Must use stack (to save $31 at the least)

Stack Frame Structure

- **Must be multiple of 8 bytes**
- **Must have space for saving argument registers $4, …, $7**
  - Even if don't store anything there
  - Used by symbolic debuggers

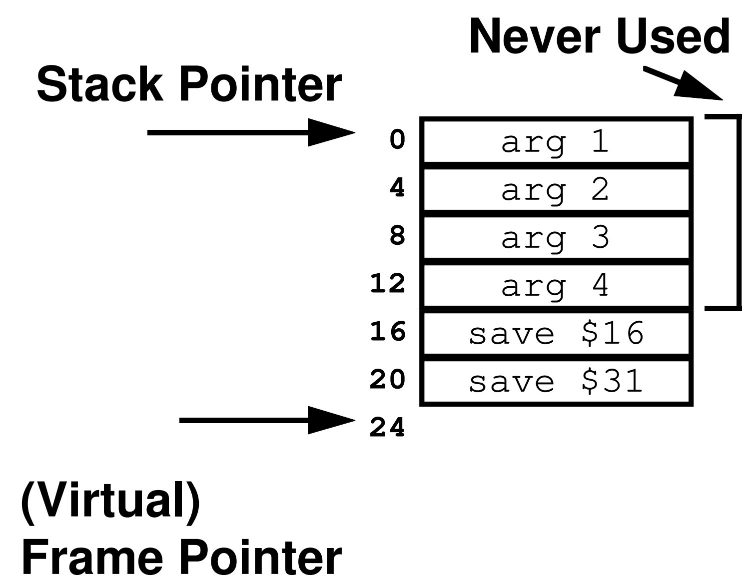
Optimized Stack Frame Example

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```

Compiled -O: Frame Setup

```
rfact:
        .frame   $sp,24,$31
        .mask    0x80010000,-4
        .fmask   0x00000000,0
        subu     $sp,$sp,24
        sw       $31,20($sp)
        sw       $16,16($sp)
```

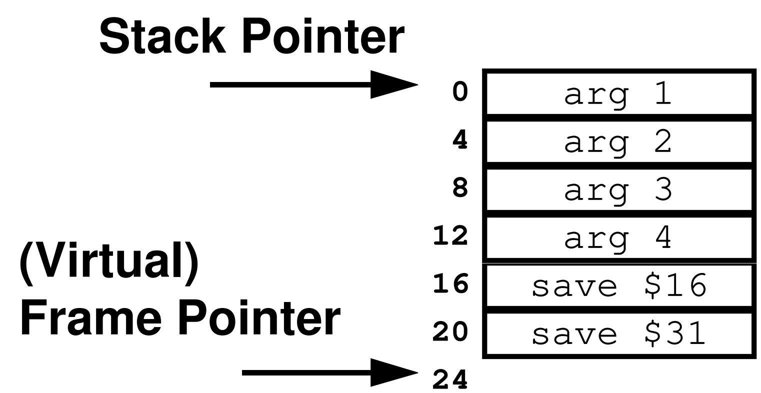


- Stack frame 24 bytes
- Virtual frame ptr at sp + 24
- Save registers $31 and $16
- Starting at sp + 24 - 4
- No floating pt. regs. used

Opt. Stack Frame Example (Cont.)

C Code

```c
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



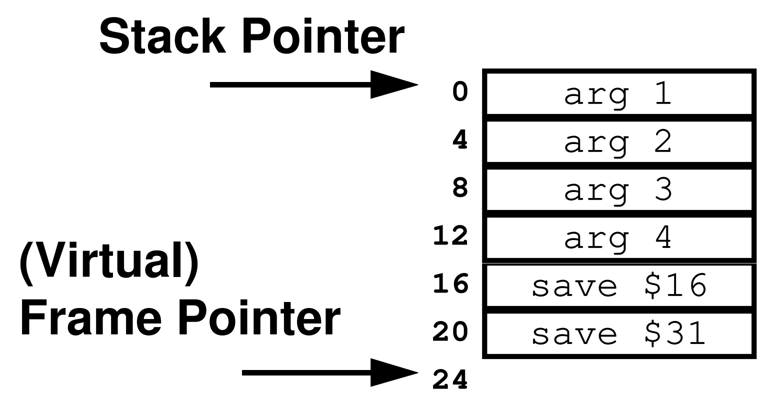
Compiled -O: Body

```
     move  $16,$4          # Save x
     slt   $2,$16,2        # if x < 2
     BNE   $2,$0,$L3       # then goto $L3
     li    $2,0x00000001   # with return val 1
     JAL   rfact           # Call rfact
     subu  $4,$16,1        # on x-1
     mult  $16,$2          # x * return val
     mflo  $2              # as return val
```

Opt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



Compiled -O: Completion

```
$L3:
    lw    $31,20($sp)
    lw    $16,16($sp)
    addu  $sp,$sp,24
    j     $31
```

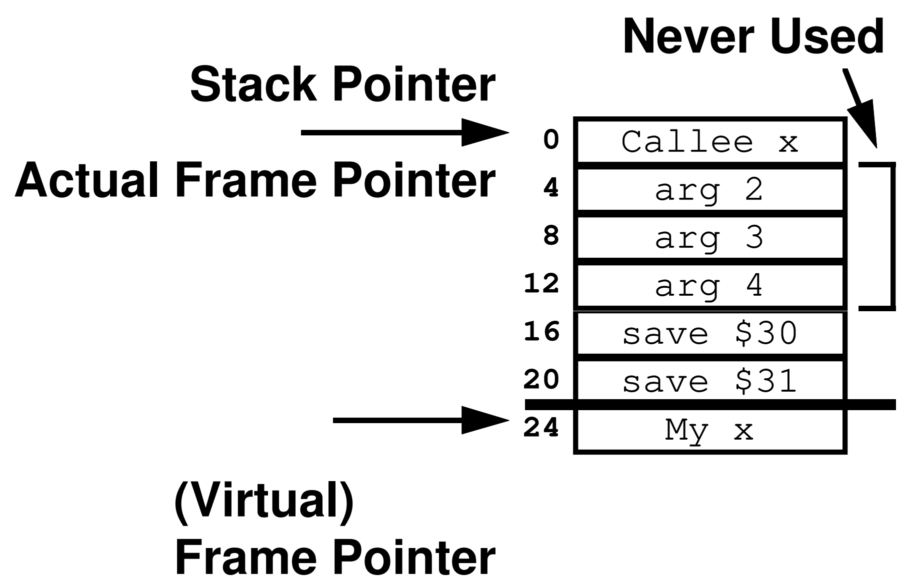
Unopt. Stack Frame Example:

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```

Compiled: Frame Setup

```
rfact:
    .frame  $fp,24,$31
    .mask   0xc0000000,-4
    .fmask  0x00000000,0
    subu    $sp,$sp,24
    sw      $31,20($sp)
    sw      $fp,16($sp)
    move     $fp,$sp
    sw       $4,24($fp)
```

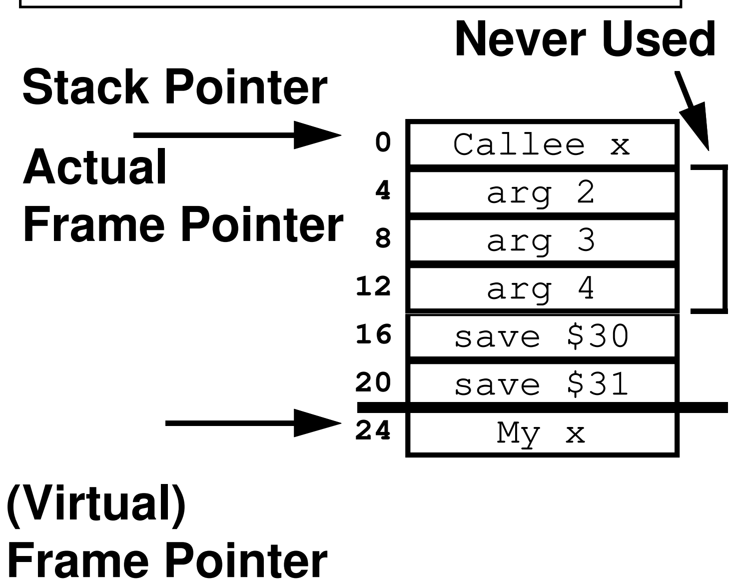


- Stack frame 24 bytes
- Actual frame pointer $fp uses $30
- Virtual frame ptr at $fp + 24
- Save registers $31 and $30
- Starting at $fp + 24 - 4
- No floating pt. regs. used

Unopt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



Compiled: Body

```
   lw      $2,24($fp)     # Get argument x
   slt     $3,$2,2        # If !(x < 2)
   beq     $3,$0,$L2      # then goto $L2
   li      $2,0x00000001  # return val 1
   j       $L1            # goto $L1
$L2:
   lw      $3,24($fp)     # Get argument x
   subu    $2,$3,1        # Subtract 1
   move    $4,$2          # assign to arg1
   jal     rfact          # Call rfact
   lw      $3,24($fp)     # Get argument x
   mult    $2,$3          # x * return val
   mflo    $2             # is return val
   j       $L1
```

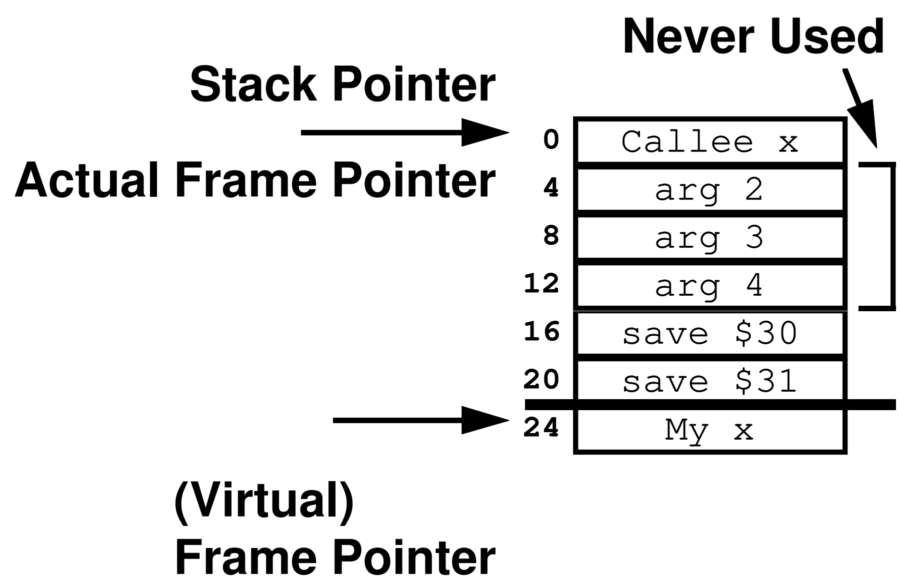
Unopt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```

Compiled: Completion

```
move    $sp,$fp
lw      $31,20($sp)
lw      $fp,16($sp)
addu    $sp,$sp,24
j       $31
```



Local Storage Example

C Code

```c
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
{
  char buf[7]; /* Not enough! */
  int i = 0;
  char *result;
  buf[i++] = c0;
  buf[i++] = c1;
  buf[i++] = c2;
  buf[i++] = c3;
  buf[i++] = c4;
  buf[i++] = c5;
  buf[i++] = c6;
  buf[i++] = 0;
  result = (char *) malloc(i);
  strcpy(result, buf);
  return result;
}
```

```c
char *do_it()
{
  return stuff_it
    ('1','5','-','7','4','0','!');
}
```

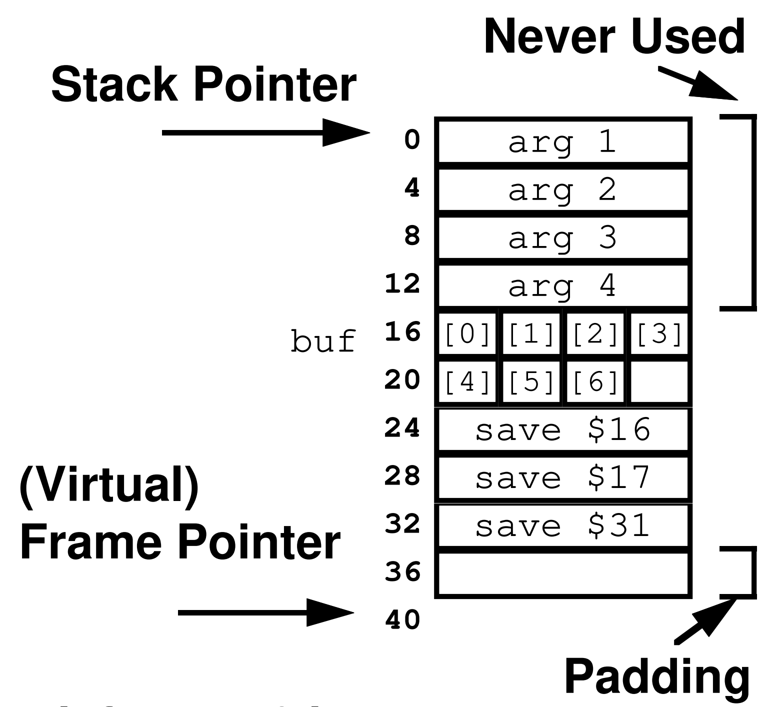
Local Storage Example

C Code: Initial

```
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
{
  char buf[7]; /* Not enough! */
  int i = 0;
  char *result;
```

Compiled -O: Frame Setup

```
stuff_it:
  .frame  $sp,40,$31
  .mask   0x80030000,-8
  .fmask  0x00000000,0
  .subu   $sp,$sp,40
  sw      $31,32($sp)
  sw      $17,28($sp)
  sw      $16,24($sp)
```



- Stack frame 40 bytes
- Virtual frame ptr at $sp + 40
- Save registers $31, $17, $16
  - Starting at $sp + 40 - 8
- No floating pt. regs. used

Local Storage Example (Cont.)

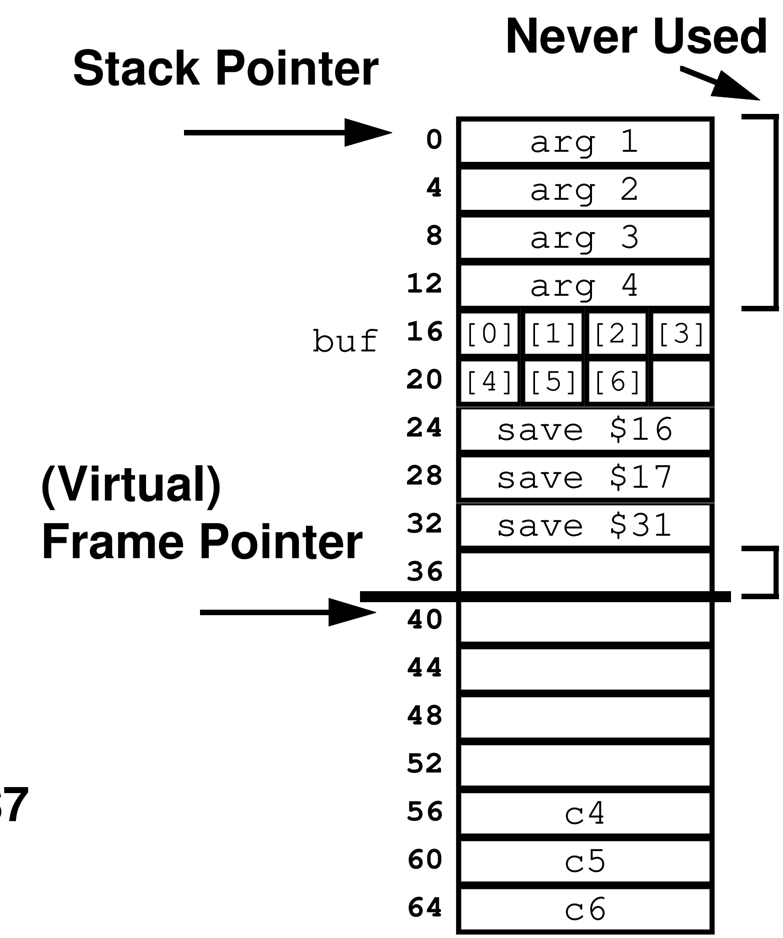
C Code: Argument Retrieval

```
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
```

Compiled -O: Args 5–7

```
lbu     $2,56($sp)
lbu     $3,60($sp)
lbu     $8,64($sp)
```

- **`c0` … `c3` passed in registers $4 … $7**



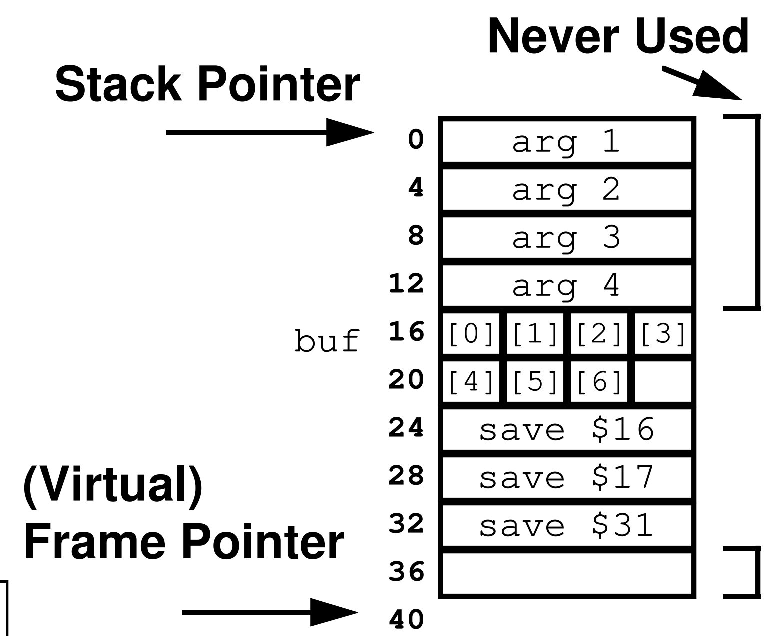
Local Storage Example (Cont.)

C Code: Local Setup

```
buf[i++] = c0;
buf[i++] = c1;
buf[i++] = c2;
buf[i++] = c3;
buf[i++] = c4;
buf[i++] = c5;
buf[i++] = c6;
buf[i++] = 0;
```

Compiled -O

```
addu    $17,$sp,16   # $17 = &buf
sb      $4,16($sp)   # buf[0] = c0
sb      $5,17($sp)   # buf[1] = c1
sb      $6,18($sp)   # buf[2] = c2
sb      $7,19($sp)   # buf[3] = c3
sb      $0,23($sp)   # buf[7] = 0  !!
sb      $2,20($sp)   # buf[4] = c4
sb      $3,21($sp)   # buf[5] = c5
sb      $8,22($sp)   # buf[6] = c6
```



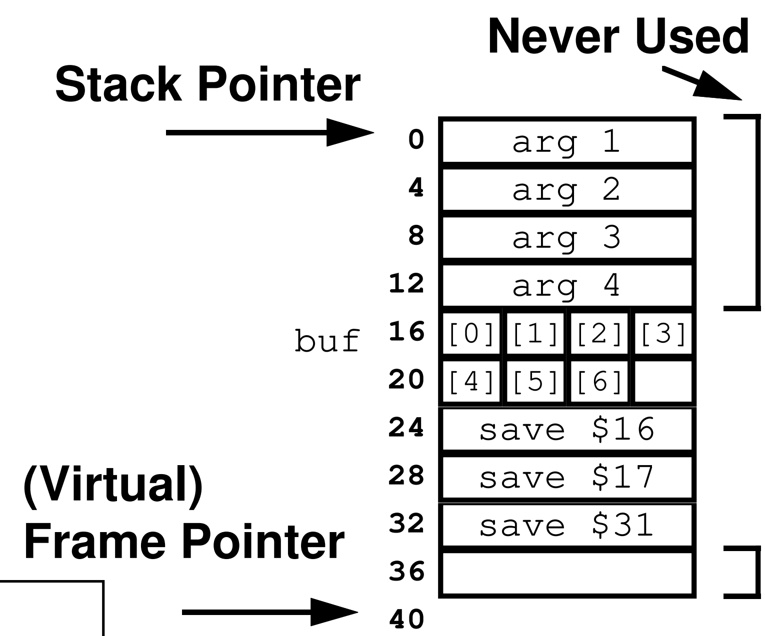
Local Storage Example (Cont.)

C Code: Calls

```
result = (char *) malloc(i);
strcpy(result, buf);
```

Compiled -O

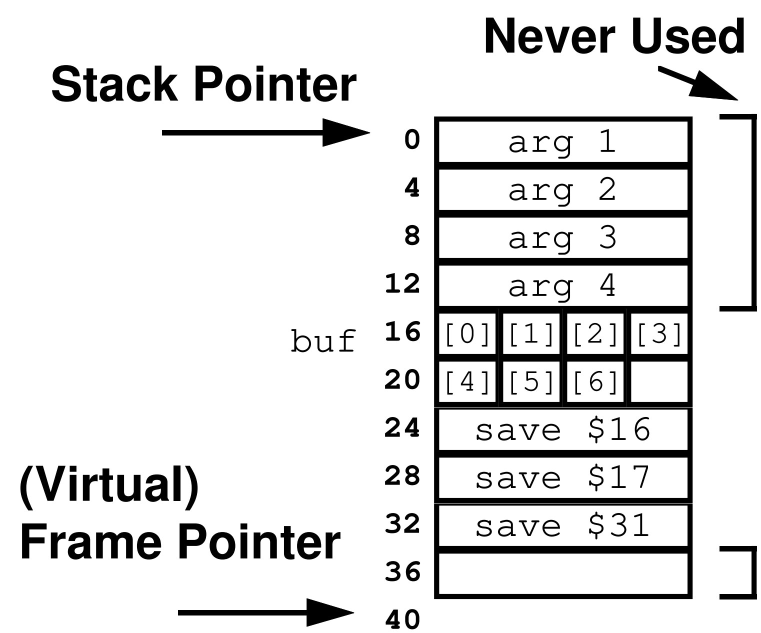
```
li      $4,0x00000008   # i = 8
jal     malloc          # malloc(i)
move    $16,$2          # $16 = result
move    $4,$16
JAL     strcpy          # strcpy(result,
move    $5,$17          #   , buf)
move    $2,$16          # return val result
```



Local Storage Example (Cont.)

Completion

```
lw      $31,32($sp)
lw      $17,28($sp)
lw      $16,24($sp)
addu    $sp,$sp,40
j       $31
```



Basic Data Types

Integral

- Stored & operated on in general registers
- Signed vs. unsigned depends on instructions used

MIPS	Bytes	C
byte	1	`[unsigned] char`
half word	2	`[unsigned] short`
word	4	`[unsigned] [long] int`
		pointer

Floating Point

- Stored & operated on in floating point registers
- Special instructions for two different precisions

MIPS	Bytes	C
single precision	4	`float`
double precision	8	`double`

Floating Point Unit

Implemented as Coprocessor 1

- Hardware to add, multiply, and divide
- Floating point data registers
- Various control & status registers

Floating Point Values

- Single precision (C `float`): 32 bits
- Double precision (C `double`): 64 bits

Floating Point Data Registers

- 32 registers, each 4 bytes
- Allocated in pairs
  - Even for single precision

`$f0`	`$f1`	Return Values
`$f2`	`$f3`	
`$f4`	`$f5`	Caller Save Temporaries: May be overwritten by called procedures
`$f6`	`$f7`	
`$f8`	`$f9`	
`$f10`	`$f11`	
`$f12`	`$f13`	Procedure arguments
`$f14`	`$f15`	
`$f16`	`$f17`	Caller Save Temporaries:
`$f18`	`$f19`	
`$f20`	`$f21`	Callee Save Temporaries: May not be overwritten by called procedures
`$f22`	`$f23`	
`$f24`	`$f25`	
`$f26`	`$f27`	
`$f28`	`$f29`	
`$f30`	`$f31`	

Floating Point Code Example

Compute Inner Product of Two Vectors

- **Single precision**

```
float inner_prodF
  (float x[], float y[], int n)
{
  int i;
  float result = 0.0;
  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
inner_prodF:
  subu    $sp,$sp,8 # Allocate stack frame
  mtc1    $0,$f4    # result = 0.0
  BLEZ    $6,$L3    # if n <= 0 goto $L3
  move    $3,$0     # i = 0
$L5:
  l.s     $f0,0($4) # $f0 = x[i]
  l.s     $f2,0($5) # $f2 = y[i]
  mul.s   $f0,$f0,$f2  # $f0 = x[i] * y[i]
  addu    $5,$5,4   # y+i++
  add.s   $f4,$f4,$f0  # result += $f0
  addu    $3,$3,1   # i++
  slt     $2,$3,$6  # if i < n
  BNE     $2,$0,$L5 # then loop
  addu    $4,$4,4   # with x+i++
$L3:
  mov.s   $f0,$f4   # return val = result
  addu    $sp,$sp,8 # Deallocate frame
  j       $31       # return
```

Double Precision

```
double inner_prodD
  (double x[], double y[],
   int n)
{
  int i;
  double result = 0.0;
  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
inner_prodD:
  # result in $f4,5
  mtc1    $0,$f4     # result = 0.0
  mtc1    $0,$f5
  subu    $sp,$sp,8 # allocate stack frame
  BLEZ    $6,$L8     # if n <= 0 goto $L8
  move    $3,$0      # i = 0
$L10:
  l.d     $f2,0($4) # $f2,3 = x[i]
  l.d     $f0,0($5) # $f0,1 = y[i]
  mul.d   $f2,$f2,$f0 # $f2,3 *= y[i]
  addu    $5,$5,8    # y+i++
  add.d   $f4,$f4,$f2 # result *= $f2,f3
  addu    $3,$3,1      # i++
  slt     $2,$3,$6     # if i < n
  BNE     $2,$0,$L10   # then loop
  addu    $4,$4,8      # with x+i++
$L8:
  mov.d   $f0,$f4      # return val = result
  addu    $sp,$sp,8    # deallocate frame
  j       $31          # return
```

Disassembled

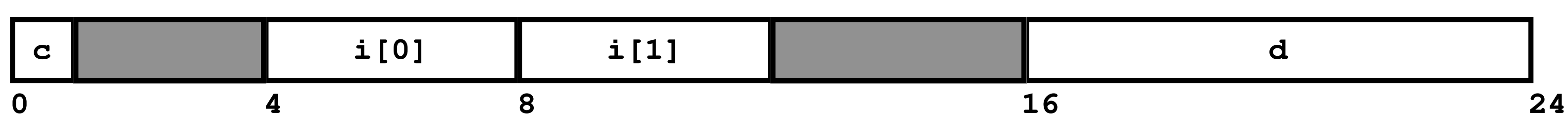
```
0x400250 <inner_prodD>:       mtc1 $zero,$f4
0x400254 <inner_prodD+4>:     mtc1 $zero,$f5
0x400258 <inner_prodD+8>:     addiu $sp,$sp,-8
0x40025c <inner_prodD+12>:    BLEZ $a2,0x400290 <inner_prodD+64>
0x400260 <inner_prodD+16>:    move $v1,$zero
0x400264 <inner_prodD+20>:    lwc1 $f2,0($a0)
0x400268 <inner_prodD+24>:    lwc1 $f3,4($a0)
0x40026c <inner_prodD+28>:    lwc1 $f0,0($a1)
0x400270 <inner_prodD+32>:    lwc1 $f1,4($a1)
0x400274 <inner_prodD+36>:    addiu $v1,$v1,1
0x400278 <inner_prodD+40>:    mul.d $f2,$f2,$f0
0x40027c <inner_prodD+44>:    slt $v0,$v1,$a2
0x400280 <inner_prodD+48>:    addiu $a1,$a1,8
0x400284 <inner_prodD+52>:    add.d $f4,$f4,$f2
0x400288 <inner_prodD+56>:    BNE $v0,$zero,0x400264 <inner_prodD+20>
0x40028c <inner_prodD+60>:    addiu $a0,$a0,8
0x400290 <inner_prodD+64>:    mov.d $f0,$f4
0x400294 <inner_prodD+68>:    JR $ra
0x400298 <inner_prodD+72>:    addiu $sp,$sp,8
```

Structure Allocation

Principles

- **Allocate space for structure elements contiguously**
- **Access fields by offsets from initial location**
  - Offsets determined by compiler

```
typedef struct {
  char c;
  int i[2];
  double d;
} struct_ele, *struct_ptr;
```



Alignment

Requirements

- **Data type requires K bytes**
- **Address must be multiple of K**

Specific Cases

- **Word data address must be multiple of 4**
- **Doubleword data address must be multiple of 8**

Reason

- **Memory accessed by (aligned) words**
  - Inefficient to load or store data that spans word boundaries
  - Virtual memory very tricky when datum spans 2 pages

Compiler

- **Inserts gaps within structure to ensure correct alignment of fields**

Structure Access

C Code

```
char struct_c(struct_ptr p)
{
  return p->c;
}
```

```
int *struct_i(struct_ptr p)
{
  return p->i;
}
```

```
int struct_i1(struct_ptr p)
{
  return p->i[1];
}
```

```
double struct_d(struct_ptr p)
{
  return p->d;
}
```

Assembler

```
  lb     $2,0($4)    # 1st byte
  j      $31
```

```
  J      $31
  addu   $2,$4,4     # addr of 4th byte
```

```
  lw     $2,8($4)    # word at 8th byte
  j      $31
```

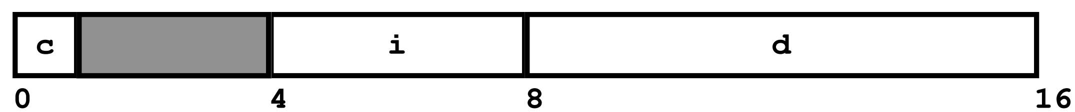
```
  l.d    $f0,16($4) # dblewd at 16th by.
  j      $31
```

Arrays vs. Pointers

Recall

- **Can access stored data either with pointer or array notation**
- **Differ in how storage allocated**
  - Array declaration allocates space for array elements
  - Pointer declaration allocates space for pointer only

```
typedef struct {
  char c;
  int *i;
  double d;
} pstruct_ele,
  *pstruct_ptr;
```



C Code for Allocation

```
pstruct_ptr pstruct_alloc(void)
{
  pstruct_ptr result = (pstruct_ptr)
           malloc(sizeof(pstruct_ele));
  result->i = (int *)
           calloc(2, sizeof(int));
  return result;
}
```

Accessing Through Pointer

C Code

```
int *pstruct_i(pstruct_ptr p)
{
  return p->i;
}
```

```
int pstruct_i1(pstruct_ptr p)
{
  return p->i[1];
}
```

Assembler

```
  lw     $2,4($4)   # word at 4th byte
  j      $31
```

```
  # i = word at 4th byte from p
  lw     $2,4($4)
  # Retrieve word at 4th byte from i
  lw     $2,4($2)
  j      $31
```

Arrays

Principles

- **Allocated by repeating allocation for array type**
- **Accessed by computing address of element**
  - Attempt to optimize
    - » Minimize use of multiplication
    - » Exploit values determined at compile time

C Code

```
/* Index into array of
   struct_ele's */
struct_ptr a_index
    (struct_ele a[], int idx)
{
  return &a[idx];
}
```

Assembler

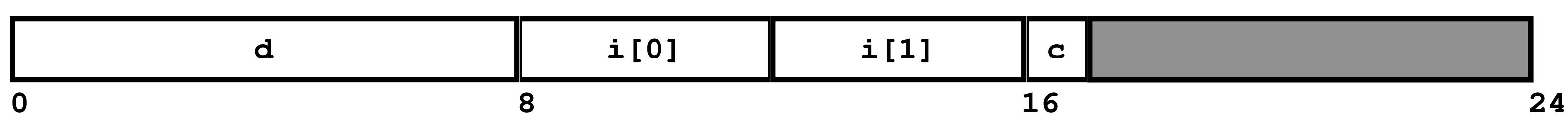
```
   sll    $2,$5,1
   addu   $2,$2,$5
   sll    $2,$2,3    # $2 = 24 * idx
   J      $31        # return
     # with a + (scaled) idx
   addu   $2,$4,$2
```

Aligning Array Elements

Requirement

- **Must make sure alignment requirements met when allocate array of structures**
- **May require inserting unused space at end of structure**

```
typedef struct {
  double d;
  int i[2];
  char c;
} rev_ele, *rev_ptr;
```



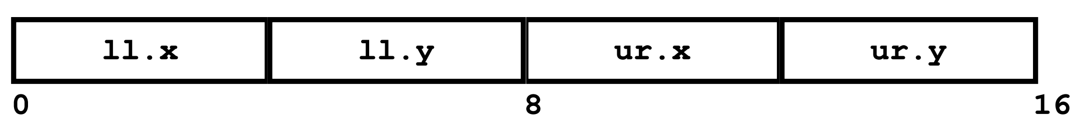
Nested Allocations

Principles

- **Can nest declarations of arrays and structures**
- **Compiler keeps track of allocation and access requirements**

```
typedef struct {
  int x;
  int y;
} point_ele, *point_ptr;

typedef struct {
  point_ele ll;
  point_ele ur;
} rect_ele, *rect_ptr;
```



Nested Allocation (cont.)

C Code

```
int area(rect_ptr r)
{
  int width = r->ur.x - r->ll.x;
  int height = r->ur.y - r->ll.y;
  return width * height;
}
```

Assembler

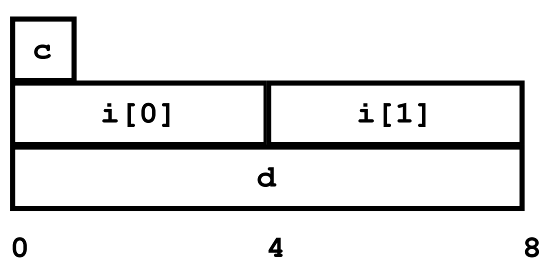
```
  lw     $2,8($4)    # $2 = ur.x
  lw     $3,0($4)    # $3 = ll.x
  subu   $2,$2,$3    # $2 = width
  lw     $3,12($4)   # $3 = ur.y
  lw     $4,4($4)    # $4 = ll.y
  subu   $3,$3,$4    # $3 = height
  mult   $2,$3
  mflo   $2          # width * height
  j      $31
```

Union Allocation

Principles

- Overlay union elements
- Allocate according to largest element
- Programmer responsible for collision avoidance

```
typedef union {
  char c;
  int i[2];
  double d;
} union_ele, *union_ptr;
```



Byte Ordering

Idea

- Bytes in word numbered 0 to 3
- Which is most (least) significant?
- Can cause problems when exchanging binary data between machines

Big Endian

- Byte 0 is most, 3 is least
- IBM 360/370, Motorola 68K, Sparc

Little Endian

- Byte 0 is least, 3 is most
- Intel x86, VAX

MIPS

- Can be configured either way
- DECStation's are little endian

Byte Ordering Example

```
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned long l[2];
} dw;
int i;
for (i = 0; i < 8; i++)
  dw.c[i] = 0xf0 + i;
printf("Characters 0-7 == [0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
       (long) dw.c[0], (long) dw.c[1], (long) dw.c[2], (long) dw.c[3],
       (long) dw.c[4], (long) dw.c[5], (long) dw.c[6], (long) dw.c[7]);
printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x]\n",
       (long) dw.s[0], (long) dw.s[1], (long) dw.s[2], (long) dw.s[3]);
printf("Longs 0-1 == [0x%x,0x%x]\n",
       dw.l[0], dw.l[1]);
```

<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4">l[1]</td></tr>
</table>

Byte Ordering Example (cont.)

Big Endian

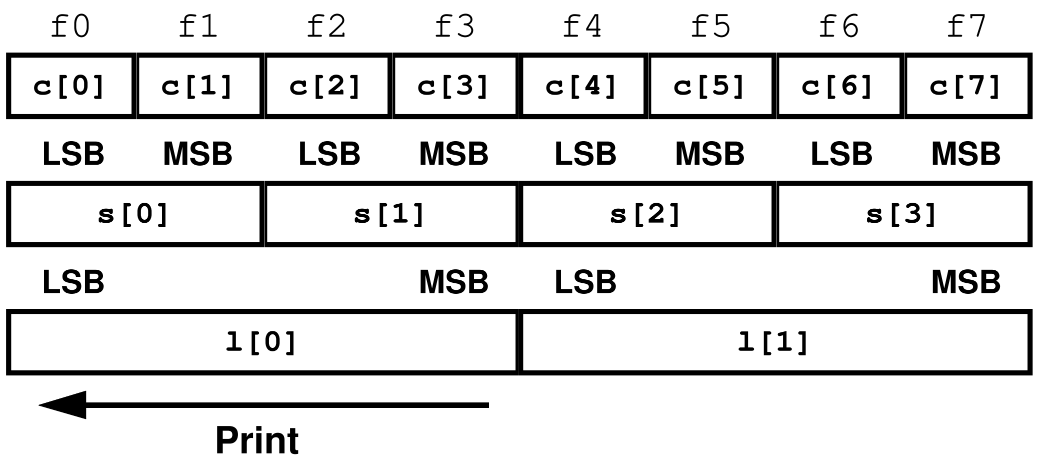
f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
MSB	LSB	MSB	LSB	MSB	LSB	MSB	LSB
s[0]		s[1]		s[2]		s[3]	
MSB			LSB	MSB			LSB
l[0]				l[1]			

Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,   0xf2f3,   0xf4f5,   0xf6f7   ]
Longs      0-1 == [0xf0f1f2f3,         0xf4f5f6f7         ]
```

Byte Ordering Example (cont.)

Little Endian



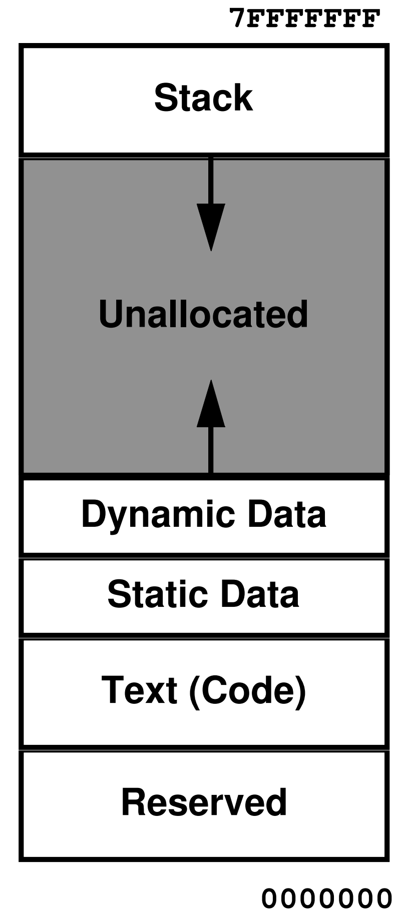
Output on DecStation:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,   0xf3f2,   0xf5f4,   0xf7f6   ]
Longs      0-1 == [0xf3f2f1f0,         0xf7f6f5f4         ]
```

MIPS Memory Layout

Segments

- **Stack**
  - Grows down from top
  - Implements runtime stack
- **Data**
  - Static space for global variables
    - » Allocation determined at compile time
  - Dynamic space for runtime allocation
    - » E.g., using malloc
- **Text**
  - Stores machine code for program
- **Reserved**
  - Used by operating system
    - » I/O devices, process info, etc.



Instruction Formats

Arithmetic

- `addu Rd, Rs, Rt`
- Similar for shift, Booleans, and comparisons

6	5	5	5	5	6
0	Rs	Rt	Rd	0	33

Constant-Manipulating

- `addi Rs, Rt, imm`
- Only have 16-bit constant

6	5	5	16
8	Rs	Rt	imm

Jump

- `j offset`

6	26
2	offset

- `beq Rs, Rt, offset`
- PC relative

6	5	5	16
4	Rs	Rt	Offset

Load/Store

- `lw Rt, Offset(Rs)`

6	5	5	16
35	Rs	Rt	Offset

Specifying Jump Targets

Jump (and link)

`j target`

	6	26	
Instr.	2	target	

	4	26	2
Dest.	HPC	target	00

High order bits of PC

Jump (and link) Register

`jr Rs`

- Rs holds dest.

6	5	15	6
0	Rs	0	8

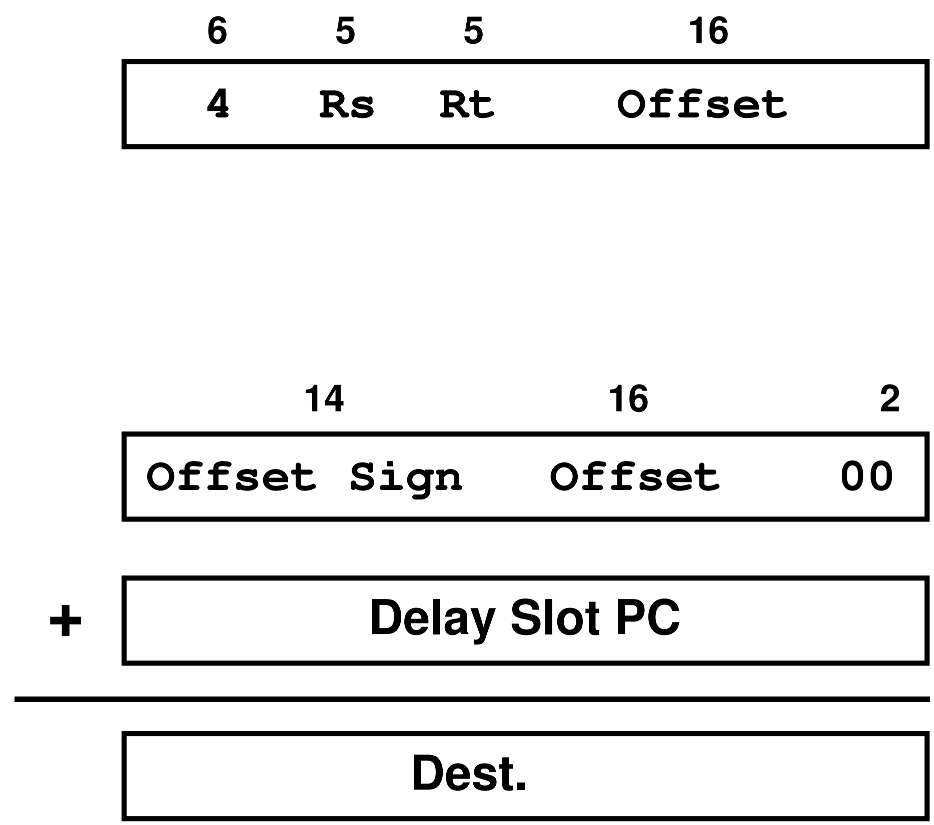
	32
Rs	Dest.

Low order two bits must be 0

Specifying Branch Targets

Branch

`beq Rs, Rt, offset`



RISC Principles Summary

Simple & Regular Instructions

- **Small number of uniform formats**
- **Each operation does just one thing**
  - Memory access, computation, conditional, etc.

Encourage Register Usage over Memory

- **Operate on register data**
  - Load/store architecture
- **Procedure linkage**

Rely on Optimizing Compiler

- **Data allocation & referencing**
- **Register allocation**
- **Improve efficiency of user's code**
- **Dealing with implementation artifacts**
  - e.g., branch delay slots