```
Arguments: a at %ebp+8, b at %ebp+12
Registers: a in %ecx, b in %ebx, result in %eax, %edx set to apb (a+b)
    movl    8(%ebp), %ecx          Get a
    movl    12(%ebp), %ebx         Get b
    movl    $1, %eax               Set result = 1
    cmpl    %ebx, %ecx             Compare a:b
    jge     .L11                   If >=, goto done
    leal    (%ebx,%ecx), %edx      Compute apb = a+b
    movl    $1, %eax               Set result = 1
  .L12:                          loop:
    imull   %edx, %eax             Compute result *= apb
    addl    $1, %ecx               Compute a++
    addl    $1, %edx               Compute apb++
    cmpl    %ecx, %ebx             Compare b:a
    jg      .L12                   If >, goto loop
  .L11:                          done:
   Return result
```

```c
int loop_while_goto(int a, int b)
{
    int result = 1;
    if (a >= b)
        goto done;
    /* apb has same value as a+b in original code */
    int apb = a+b;
 loop:
    result *= apb;
    a++;
    apb++;
    if (b > a)
        goto loop;
 done:
    return result;
}
```

```
Arguments: a at %ebp+8, b at %ebp+12
Registers: a in %ecx, b in %ebx, result in %eax, %edx set to apb (a+b)
    movl    8(%ebp), %ecx          Get a
    movl    12(%ebp), %ebx         Get b
    movl    $1, %eax               Set result = 1
    cmpl    %ebx, %ecx             Compare a:b
    jge     .L11                   If >=, goto done
    leal    (%ebx,%ecx), %edx      Compute apb = a+b
    movl    $1, %eax               Set result = 1
  .L12:                          loop:
    imull   %edx, %eax             Compute result *= apb
    addl    $1, %ecx               Compute a++
    addl    $1, %edx               Compute apb++
    cmpl    %ecx, %ebx             Compare b:a
    jg      .L12                   If >, goto loop
  .L11:                          done:
    Return result
```

```
.type   _Z15loop_while_gotoii, @function
_Z15loop_while_gotoii:
.LFB31:
        .cfi_startproc
        pushl   %ebp
        .cfi_def_cfa_offset 8
        movl    %esp, %ebp
        .cfi_offset 5, -8
        .cfi_def_cfa_register 5
        pushl   %ebx
        movl    8(%ebp), %edx
        movl    12(%ebp), %ebx
        .cfi_offset 3, -12
        movl    $1, %eax
        cmpl    %ebx, %edx
        jge     .L2
        leal    (%ebx,%edx), %ecx
.L3:
        imull   %ecx, %eax
        addl    $1, %edx
        addl    $1, %ecx
        cmpl    %edx, %ebx
        jg      .L3
.L2:
        popl    %ebx
        .cfi_restore 3
        popl    %ebp
        .cfi_restore 5
        .cfi_def_cfa 4, 4
        ret
        .cfi_endproc
```

```
int E[10]; //an array of integers
int i; //index into array
```

E is in %edx, i is in %ecx

Move *something* into %eax

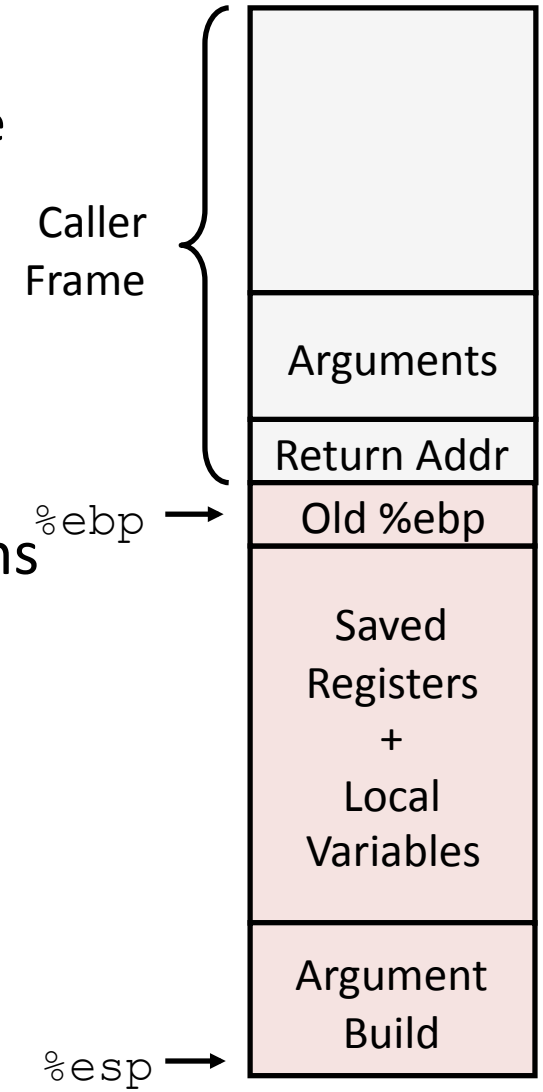
E	int *	movl %edx, %eax
E[0]	int	movl (%edx), %eax
E[i]	int	movl (%edx, %ecx, 4), %eax
&E[2]	int*	leal 8(%edx), %eax
&E[i]-E	int	movl %ecx, %eax

#define vs. const for array allocation

- const actually not in K&R
- const needs a lookup
- #define is a pre-processer step
- #define doesn’t need a type!

IA 32 Procedure Summary

- The Stack Makes Recursion Work
  - Private storage for each *instance* of procedure call
    - Instantiations don't clobber each other
    - Addressing of locals + arguments can be relative to stack positions
  - Managed by stack discipline
    - Procedures return in inverse order of calls
- IA32 Procedures Combination of Instructions + Conventions
  - Call / Ret instructions
  - Register usage conventions
    - Caller / Callee save
    - **`%ebp`** and **`%esp`**
  - Stack frame organization conventions



```
1   int proc(void)
2   {
3       int x,y;
4       scanf("%x %x", &y, &x);
5       return x-y;
6   }
```

```
1   proc:
2     pushl   %ebp
3     movl    %esp, %ebp
4     subl    $40, %esp
5     leal    -4(%ebp), %eax
6     movl    %eax, 8(%esp)
7     leal    -8(%ebp), %eax
8     movl    %eax, 4(%esp)
9     movl    $.LC0, (%esp)     Pointer to string "%x %x"
10    call    scanf
      Diagram stack frame at this point
11    movl    -4(%ebp), %eax
12    subl    -8(%ebp), %eax
13    leave
14    ret
```

Register	Value
%esp	0x800040
%ebp	0x800060

Suppose `proc` calls `scanf` (line 10), and that `scanf` reads values 0x46 and 0x53 from the standard input. Assume that the string "%x %x" is stored at memory location 0x300070.

A. What value does %ebp get set to on line 3?

B. What value does %esp get set to on line 4?

C. At what addresses are local variables x and y stored?

D. Draw a diagram of the stack frame for `proc` right after `scanf` returns. Include as much information as you can about the addresses and the contents of the stack frame elements.

E. Indicate the regions of the stack frame that are not used by `proc`.

A. We started with %esp having value 0x800040. The pushl instruction on line 2 decrements the stack pointer by 4, giving 0x80003C, and this becomes the new value of %ebp.

B. Line 4 decrements the stack pointer by 40 (hex 0x28), yielding 0x800014.

C. We can see how the two leal instructions (lines 5 and 7) compute the arguments to pass to scanf, while the two movl instructions (lines 6 and 8) store them on the stack. Since the function arguments appear on the stack at increasingly positive offsets from %esp, we can conclude that line 5 computes &x, while line 7 computes line &y. These have values 0x800038 and 0x800034, respectively.

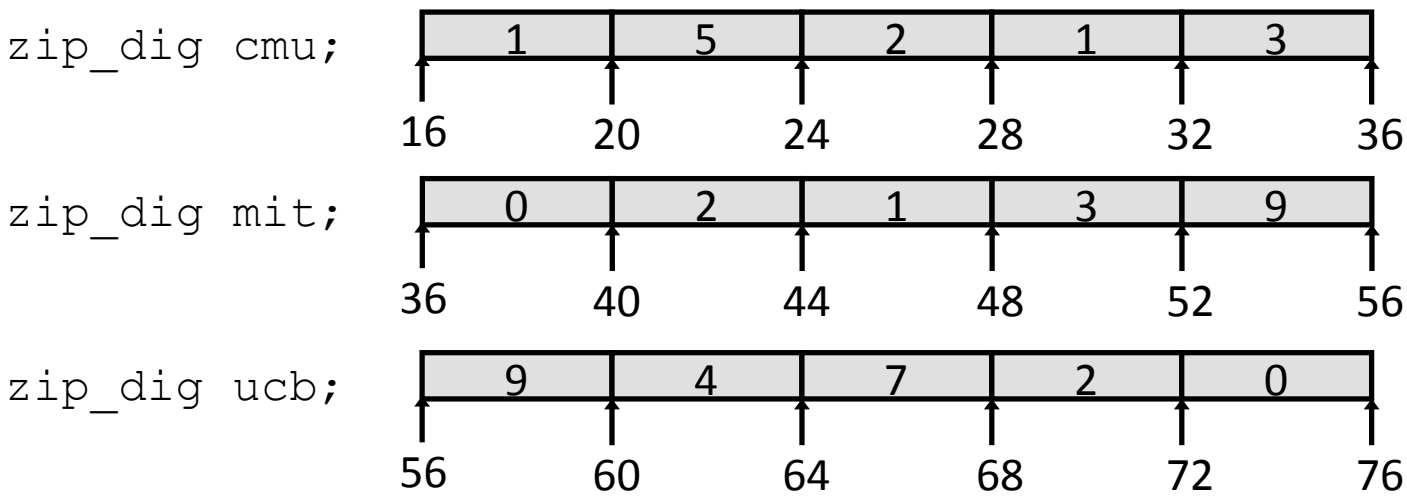
D. The stack frame has the following structure and contents:

0x80003C	0x800060	← %ebp
0x800038	0x53	x
0x800034	0x46	y
0x800030		
0x80002C		
0x800028		
0x800024		
0x800020		
0x80001C	0x800038	
0x800018	0x800034	
0x800014	0x300070	← %esp

```
1   proc:
2     pushl   %ebp
3     movl    %esp, %ebp
4     subl    $40, %esp
5     leal    -4(%ebp), %eax
6     movl    %eax, 8(%esp)
7     leal    -8(%ebp), %eax
8     movl    %eax, 4(%esp)
9     movl    $.LC0, (%esp)     Pointer to string "%x %x"
10    call    scanf
    Diagram stack frame at this point
11    movl    -4(%ebp), %eax
12    subl    -8(%ebp), %eax
13    leave
14    ret
```

E. Byte addresses 0x800020 through 0x800033 are unused.

Referencing Examples



- Reference Address Value Guaranteed?

Reference	Address	Value	Guaranteed?
`mit[3]`	`36 + 4* 3 = 48`	`3`	Yes
`mit[5]`	`36 + 4* 5 = 56`	`9`	No
`mit[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

  - No bound checking
  - Out of range behavior implementation-dependent
  - No guaranteed relative allocation of different arrays

Optimizing Dynamic Array Multiplication

- Optimizations
  - Performed when set optimization level to **`-O2`**
- Code Motion
  - Expression **`i*n`** can be computed outside loop
- Strength Reduction
  - Incrementing **`j`** has effect of incrementing **`j*n+k`** by **`n`**
- Operations count
  - 4 adds, 1 mult
- Compiler can optimize regular access patterns

```
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n+j] * b[j*n+k];
  return result;
}
```

```
{
  int j;
  int result = 0;
  int iTn = i*n;
  int jTnPk = k;
  for (j = 0; j < n; j++) {
    result +=
      a[iTn+j] * b[jTnPk];
    jTnPk += n;
  }
  return result;
}
```

Structures

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

Memory Layout

- Concept
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Members may be of different types
- Accessing Structure Member

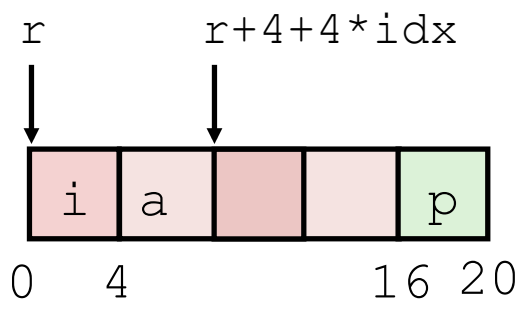
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

IA32 Assembly

```
# %eax = val
# %edx = r
movl %eax,(%edx)    # Mem[r] = val
```

Generating Pointer to Structure Member

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



- Generating Pointer to Array Element
  - Offset of each structure member determined at compile time

```
int *find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

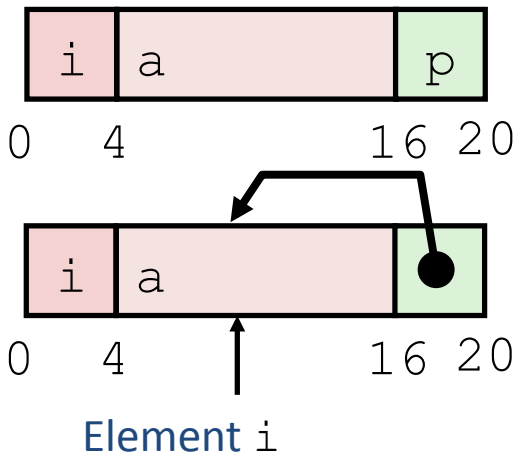
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax   # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```

Structure Referencing (Cont.)

- C Code

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

```
void set_p(struct rec *r)
{
  r->p = &r->a[r->i];
}
```

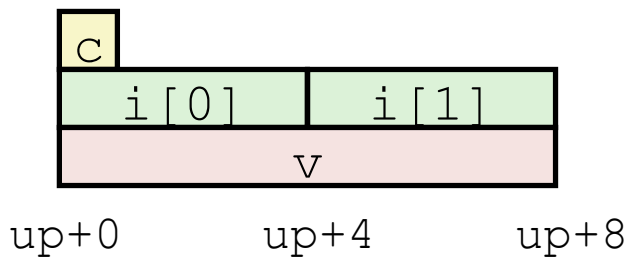



```
 # %edx = r
 movl (%edx),%ecx          # r->i
 leal 0(,%ecx,4),%eax      # 4*(r->i)
 leal 4(%edx,%eax),%eax # r+4+4*(r->i)
 movl %eax,16(%edx)        # Update r->p
```

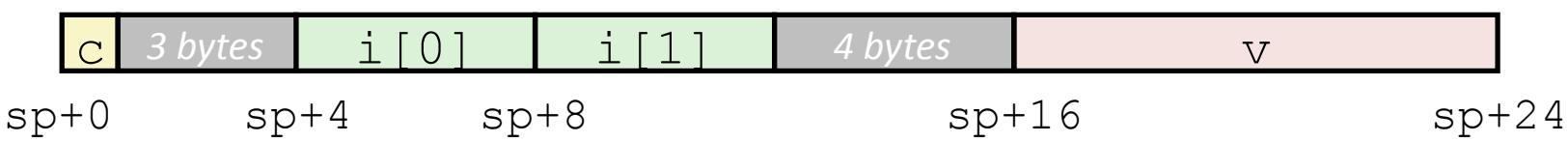
Union Allocation

- Allocate according to largest element
- Can only use ones field at a time

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```

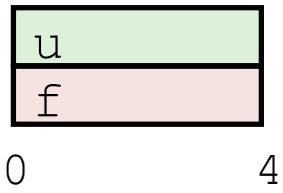



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```




```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

Same as `(float) u` ?

Same as `(unsigned) f` ?

Alignment

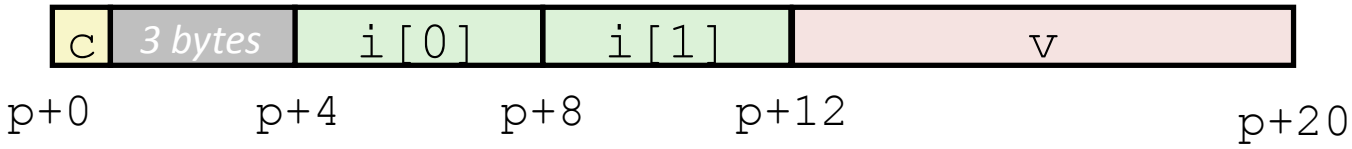
- Aligned Data
  - Primitive data type requires K bytes
  - Address must be multiple of K
  - Required on some machines; advised on IA32
    - treated differently by IA32 Linux, x86-64 Linux, and Windows!
- Motivation for Aligning Data
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory very tricky when datum spans 2 pages
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields

Specific Cases of Alignment (IA32)

- 1 byte: `char, …`
  - no restrictions on address
- 2 bytes: `short`, …
  - lowest 1 bit of address must be 0_2
- 4 bytes: `int`, `float`, `char *`, …
  - lowest 2 bits of address must be 00_2
- 8 bytes: `double`, …
  - Windows (and most other OS's & instruction sets):
    - lowest 3 bits of address must be 000_2
  - Linux:
    - lowest 2 bits of address must be 00_2
    - i.e., treated the same as a 4-byte primitive data type
- 12 bytes: `long double`
  - Windows, Linux:
    - lowest 2 bits of address must be 00_2
    - i.e., treated the same as a 4-byte primitive data type

Different Alignment Conventions

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

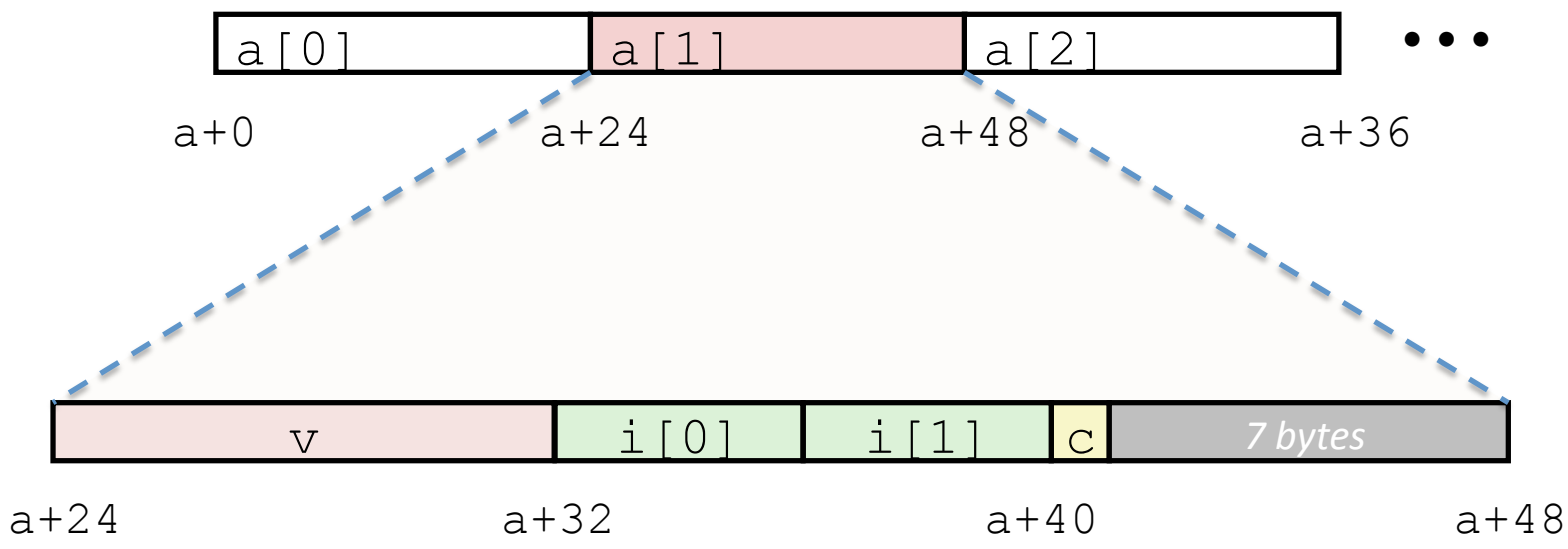


- IA32 Linux
  - K = 4; **`double`** treated like a 4-byte data type

Arrays of Structures

- Satisfy alignment requirement for every element

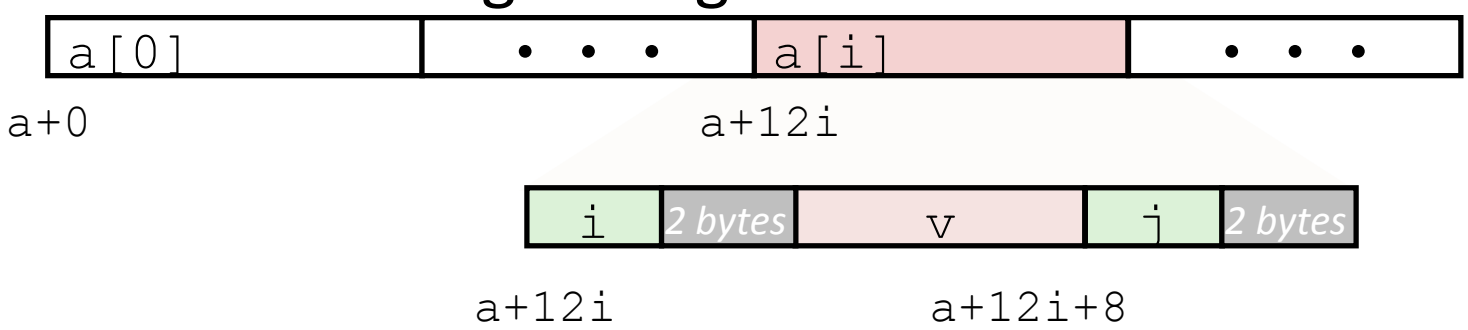
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```

- Compute array offset 12i
- Compute offset 8 with structure
- Assembler gives offset a+8
  - Resolved during linking




```
short get_j(int idx)
{
  return a[idx].j;
}
```

```
# %eax = idx
leal (%eax,%eax,2),%eax # 3*idx
movswl a+8(,%eax,4),%eax
```

Pointer Code

Recursive Procedure

```
void s_helper
  (int x, int *accum)
{
  if (x <= 1)
    return;
  else {
    int z = *accum * x;
    *accum = z;
    s_helper (x-1,accum);
  }
}
```

Top-Level Call

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Pass pointer to update location

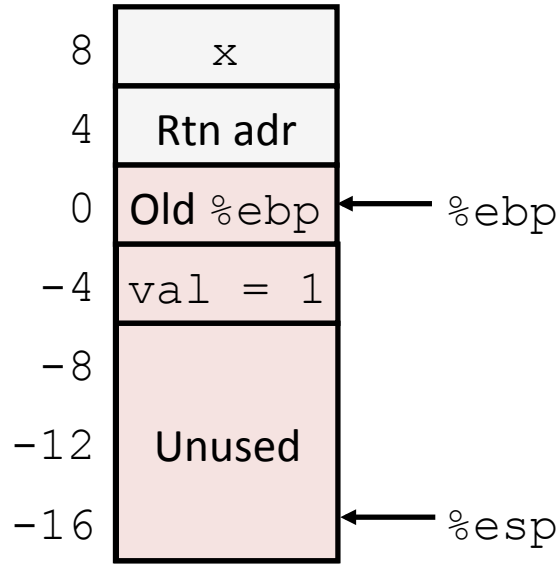
Creating & Initializing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Variable `val` must be stored on stack
  - Because: Need to create pointer to it
- Compute pointer as `-4(%ebp)`
- Push on stack as second argument

Initial part of `sfact`

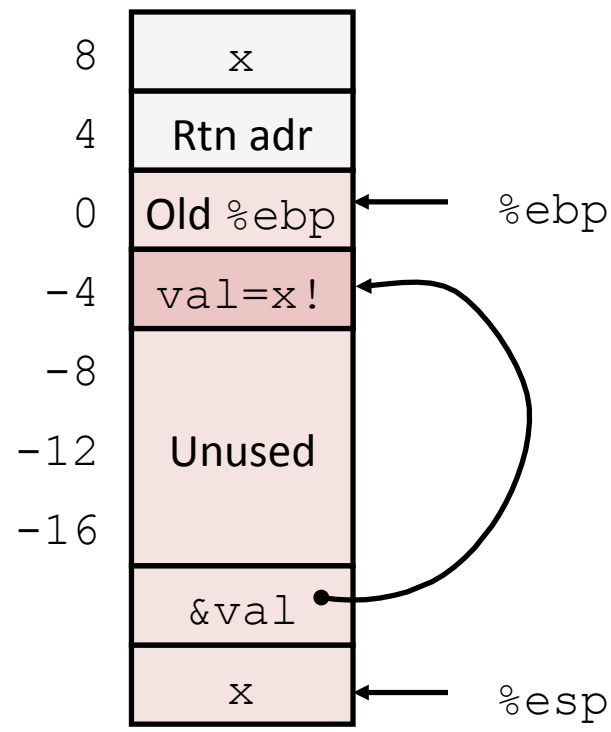
```
_sfact:
   pushl %ebp          # Save %ebp
   movl %esp,%ebp      # Set %ebp
   subl $16,%esp       # Add 16 bytes
   movl 8(%ebp),%edx   # edx = x
   movl $1,-4(%ebp)    # val = 1
```



Passing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



Calling `s_helper` from `sfact`

```
   leal -4(%ebp),%eax  # Compute &val
   pushl %eax          # Push on stack
   pushl %edx          # Push x
   call s_helper       # call
   movl -4(%ebp),%eax  # Return val
   • • •               # Finish
```

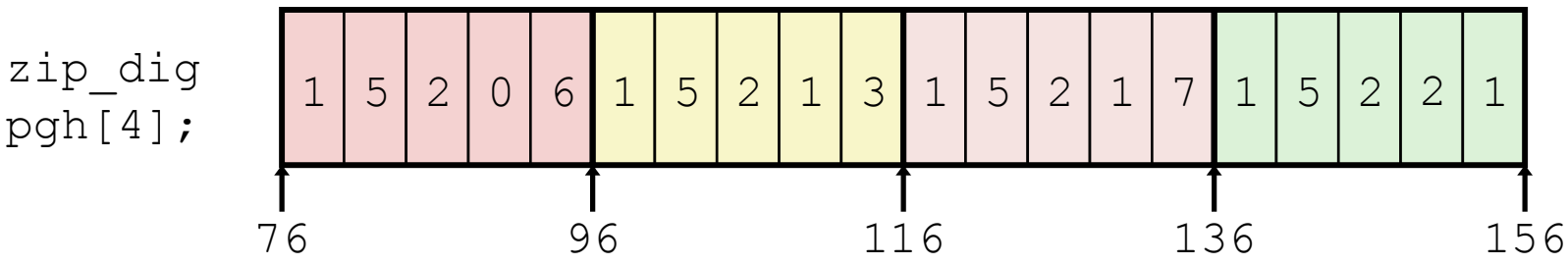
And who thought this was a good idea?

- Pointers!
- Pointers to functions!?
  - `void (*foo)(int);`
  - foo is a pointer to a function taking one argument, an integer, and that returns void
  - `void *(*foo)(int *);`
  - foo is a pointer to a function that returns a void * (e.g., a pointer to an *unknown* data type) and takes an int *

- Pointers to arrays of functions!?!
- Pointers to pointers to functions with pointers!?!?

Nested Array Example

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



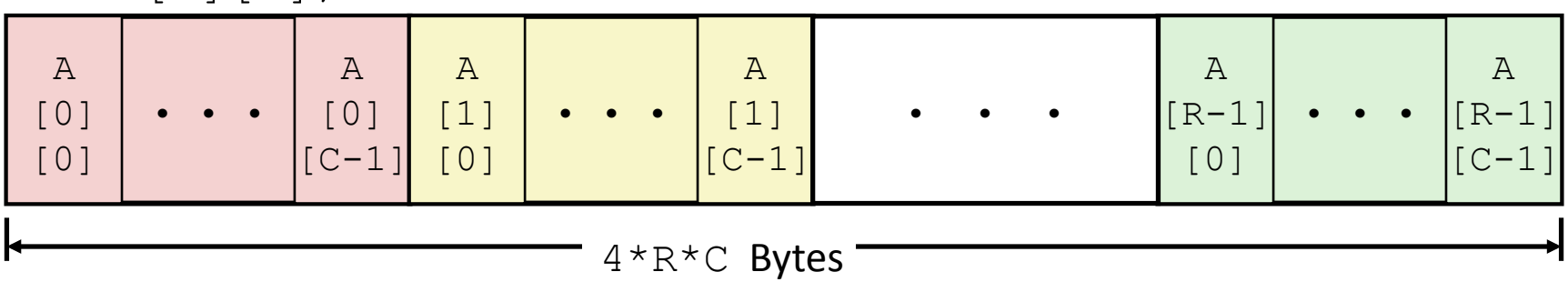
- "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable **`pgh`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**'s, allocated contiguously
- "Row-Major" ordering of all elements guaranteed

Multidimensional (Nested) Arrays

- Declaration
  T **A**[*R*][*C*];
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes
- Array Size
  - *R* * *C* * *K* bytes
- Arrangement
  - Row-Major Ordering

$$\begin{bmatrix} A[0][0] & \cdots & A[0][C-1] \\ \vdots & & \vdots \\ A[R-1][0] & \cdots & A[R-1][C-1] \end{bmatrix}$$

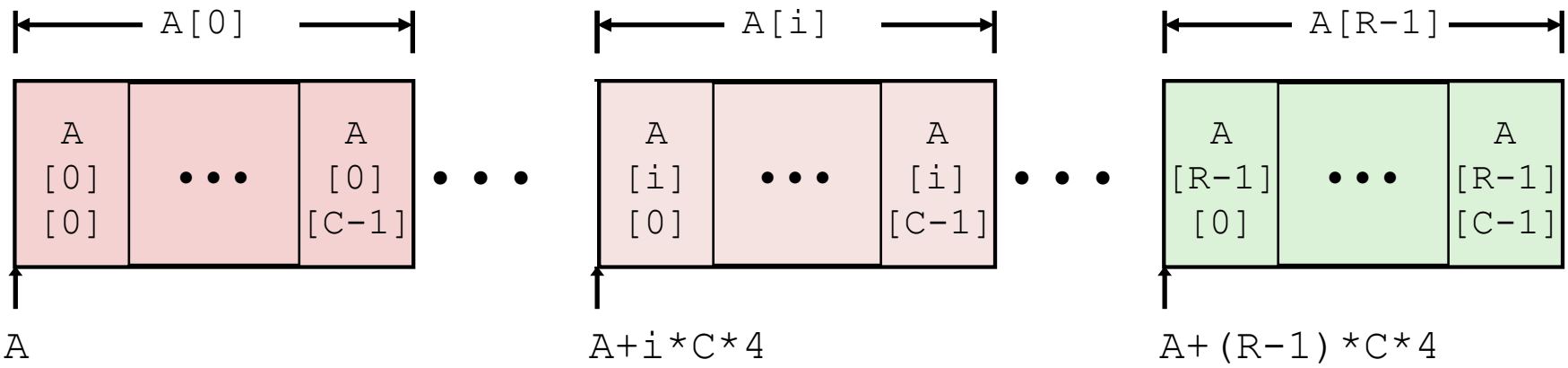
```
int A[R][C];
```



Nested Array Row Access

- Row Vectors
  - **`A[i]`** is array of *C* elements
  - Each element of type *T* requires *K* bytes
  - Starting address **`A +`** *i* * (*C* * *K*)

```
int A[R][C];
```



Nested Array Row Access Code

```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

```
  # %eax = index
   leal (%eax,%eax,4),%eax
   leal pgh(,%eax,4),%eax
```

Nested Array Row Access Code

```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

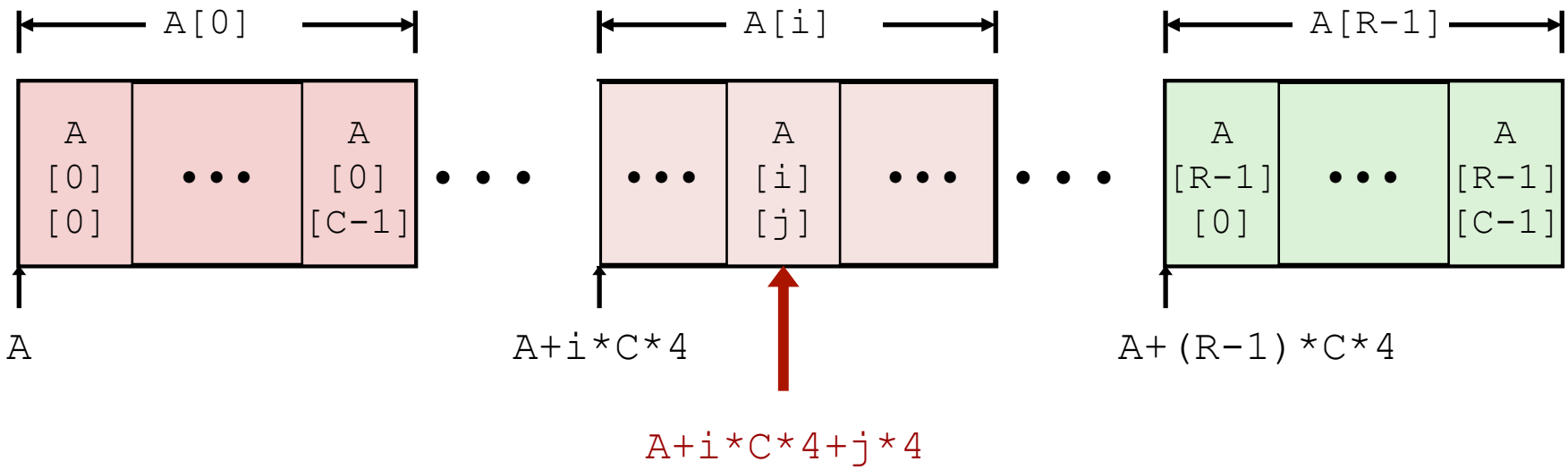
```
  # %eax = index
   leal (%eax,%eax,4),%eax # 5 * index
   leal pgh(,%eax,4),%eax  # pgh + (20 * index)
```

- Row Vector
  - **`pgh[index]`** is array of 5 **`int`**'s
  - Starting address **`pgh+20*index`**
- IA32 Code
  - Computes and returns address
  - Compute as **`pgh + 4*(index+4*index)`**

Nested Array Row Access

- Array Elements
  - **`A[i][j]`** is element of type *T*, which requires *K* bytes
  - Address **`A +`** $i * (C * K) + j * K = A + (i * C + j) * K$

```
int A[R][C];
```



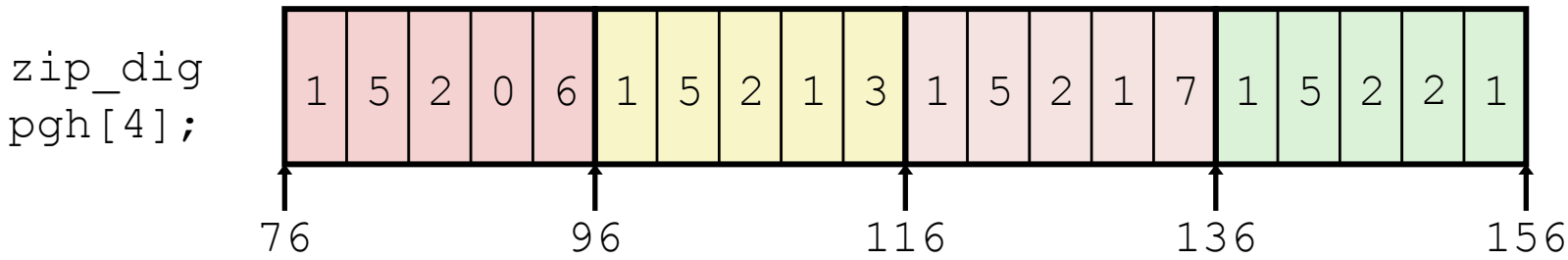
Nested Array Element Access Code

```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

```
 # %ecx = dig
 # %eax = index
 leal 0(,%ecx,4),%edx          # 4*dig
 leal (%eax,%eax,4),%eax       # 5*index
 movl pgh(%edx,%eax,4),%eax    # *(pgh + 4*dig + 20*index)
```

- Array Elements
  - **`pgh[index][dig]`** is **`int`**
  - Address: **`pgh + 20*index + 4*dig`**
- IA32 Code
  - Computes address **`pgh + 4*dig + 4*(index+4*index)`**
  - **`movl`** performs memory reference

Strange Referencing Examples



- Reference Address

Value Guaranteed?

`pgh[3][3]`

`pgh[2][5]`

`pgh[2][-1]`

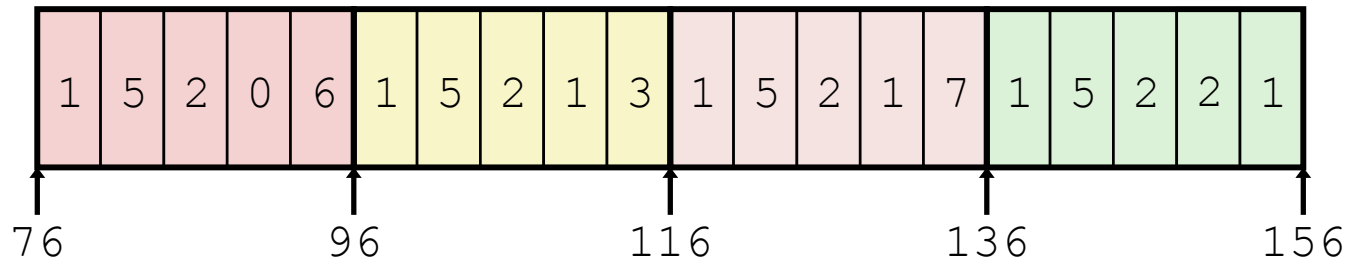
`pgh[4][-1]`

`pgh[0][19]`

`pgh[0][-1]`

Strange Referencing Examples

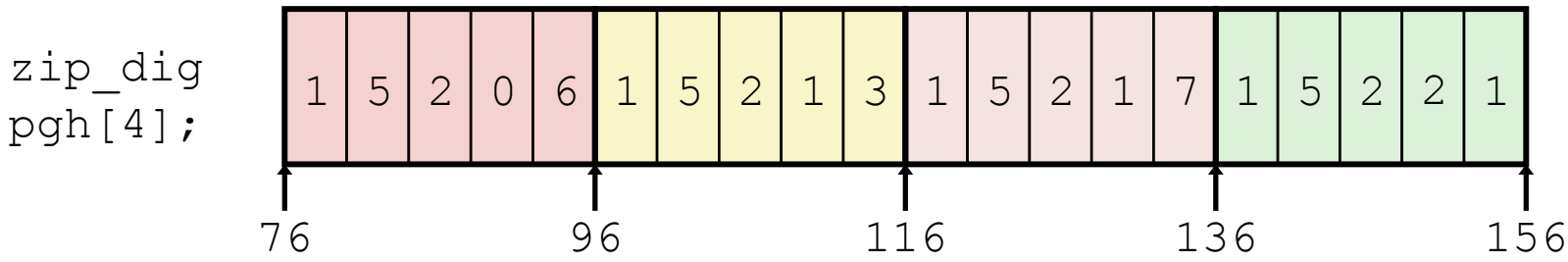
```
zip_dig
pgh[4];
```



- Reference Address

		Value Guaranteed?
pgh[3][3]	**76+20*3+4*3 = 148**	**2** Yes
pgh[2][5]		
pgh[2][-1]		
pgh[4][-1]		
pgh[0][19]		
pgh[0][-1]		

Strange Referencing Examples



- Reference Address Value Guaranteed?

`pgh[3][3]`	`76+20*3+4*3 = 148`	`2`	Yes
`pgh[2][5]`	`76+20*2+4*5 = 136`	`1`	Yes
`pgh[2][-1]`	`76+20*2+4*-1 = 112`	`3`	Yes
`pgh[4][-1]`	`76+20*4+4*-1 = 152`	`1`	Yes
`pgh[0][19]`	`76+20*0+4*19 = 152`	`1`	Yes
`pgh[0][-1]`	`76+20*0+4*-1 = 72`	`??`	No

  – Code does not do any bounds checking
  – Ordering of elements within array guaranteed