Machine-Level Programming IV: x86-64 Procedures, Data

15-213 / 18-213: Introduction to Computer Systems
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Today

- **Procedures (x86-64)**
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access

x86-64 Integer Registers

%rax	%eax	%r8	%r8d
%rbx	%ebx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%edx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

- Twice the number of registers
- Accessible as 8, 16, 32, 64 bits

x86-64 Integer Registers: Usage Conventions

`%rax`	Return value	`%r8`	Argument #5
`%rbx`	Callee saved	`%r9`	Argument #6
`%rcx`	Argument #4	`%r10`	Caller saved
`%rdx`	Argument #3	`%r11`	Caller Saved
`%rsi`	Argument #2	`%r12`	Callee saved
`%rdi`	Argument #1	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Callee saved	`%r15`	Callee saved

x86-64 Registers

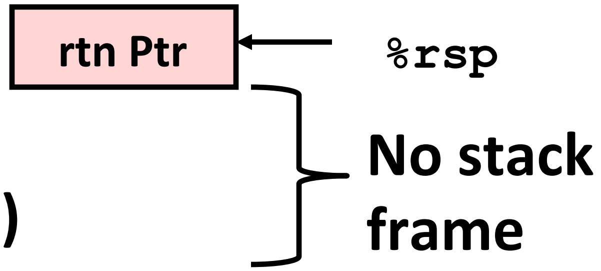
- **Arguments passed to functions via registers**
  - If more than 6 integral parameters, then pass rest on stack
  - These registers can be used as caller-saved as well
- **All references to stack frame via stack pointer**
  - Eliminates need to update `%ebp/%rbp`
- **Other Registers**
  - 6 callee saved
  - 2 caller saved
  - 1 return value (also usable as caller saved)
  - 1 special (stack pointer)

x86-64 Long Swap

```
void swap_l(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
   movq   (%rdi), %rdx
   movq   (%rsi), %rax
   movq   %rax, (%rdi)
   movq   %rdx, (%rsi)
   ret
```

- **Operands passed in registers**
  - First (**`xp`**) in **`%rdi`**, second (**`yp`**) in **`%rsi`**
  - 64-bit pointers
- **No stack operations required (except `ret`)**
- **Avoiding stack**
  - Can hold all local information in registers

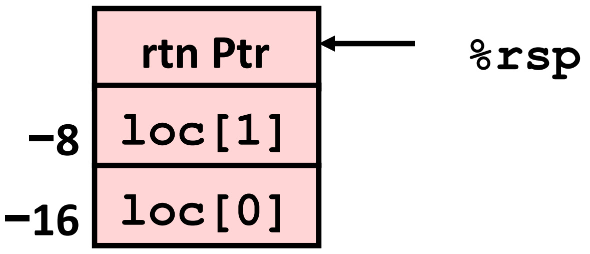


x86-64 Locals in the Red Zone

```
/* Swap, using local array */
void swap_a(long *xp, long *yp)
{
    volatile long loc[2];
    loc[0] = *xp;
    loc[1] = *yp;
    *xp = loc[1];
    *yp = loc[0];
}
```

```
swap_a:
  movq   (%rdi), %rax
  movq   %rax, -16(%rsp)
  movq   (%rsi), %rax
  movq   %rax, -8(%rsp)
  movq   -8(%rsp), %rax
  movq   %rax, (%rdi)
  movq   -16(%rsp), %rax
  movq   %rax, (%rsi)
  ret
```

- **Avoiding Stack Pointer Change**
  - Can hold all information within small window beyond stack pointer

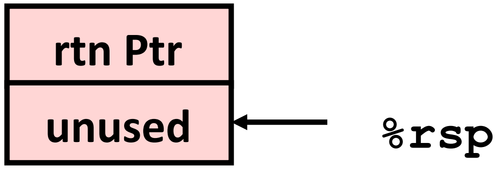


x86-64 NonLeaf with Unused Stack Frame

```
/* Swap a[i] and a[j] */
void swap_ele(long a[],
              long i, long j) {
  swap(&a[i], &a[j]);
}
```

- No values held while swap being invoked
- No callee save registers needed
- 8 bytes allocated, but not used

```
swap_ele:
  subq     $8, %rsp               # Allocate 8 bytes
  movq     %rsi, %rax             # Copy i
  leaq     (%rdi,%rdx,8), %rsi    # &a[i]
  leaq     (%rdi,%rax,8), %rdi    # &a[j]
  call     swap
  addq     $8, %rsp               # Deallocate
  ret
```

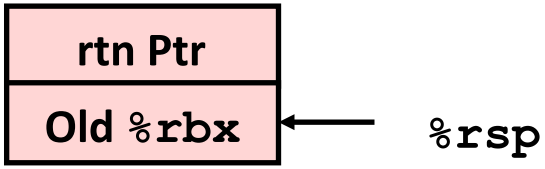


x86-64 Stack Frame Example #1

```
/* Swap a[i] and a[j]
   Compute difference */
void swap_ele_diff(long a[],
              long i, long j) {
  long diff = a[j] - a[i];
  swap(&a[i], &a[j]);
  return diff;
}
```

```
swap_ele_diff:
  pushq    %rbx
  leaq     (%rdi,%rdx,8), %rdx
  leaq     (%rdi,%rsi,8), %rdi
  movq     (%rdx), %rbx
  subq     (%rdi), %rbx
  movq     %rdx, %rsi
  call     swap
  movq     %rbx, %rax
  popq     %rbx
  ret
```

- Keeps `diff` in callee save register
- Uses push & pop to save/ restore

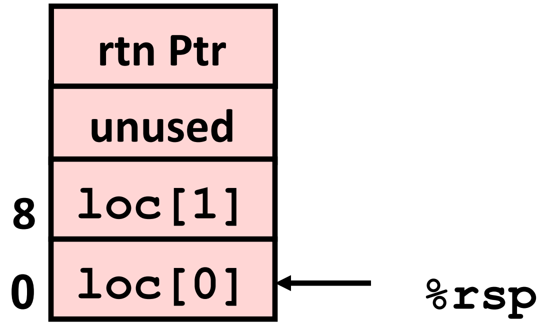


x86-64 Stack Frame Example #2

```
/* Swap a[i] and a[j] */
void swap_ele_l(long a[],
                long i, long j) {
    long *loc[2];
    long b = i & 0x1;
    loc[b] = &a[i];
    loc[1-b] = &a[j];
    swap(loc[0], loc[1]);
}
```

- Must allocate space on stack for array `loc`
- Uses `subq` to allocate, `addq` to deallocate

```
swap_ele_l:
   subq    $24, %rsp
   movq    %rsi, %rax
   andl    $1, %eax
   leaq    (%rdi,%rsi,8), %rcx
   movq    %rcx, (%rsp,%rax,8)
   movl    $1, %ecx
   subq    %rax, %rcx
   leaq    (%rdi,%rdx,8), %rdx
   movq    %rdx, (%rsp,%rcx,8)
   movq    8(%rsp), %rsi
   movq    (%rsp), %rdi
   call    swap
   addq    $24, %rsp
   ret
```

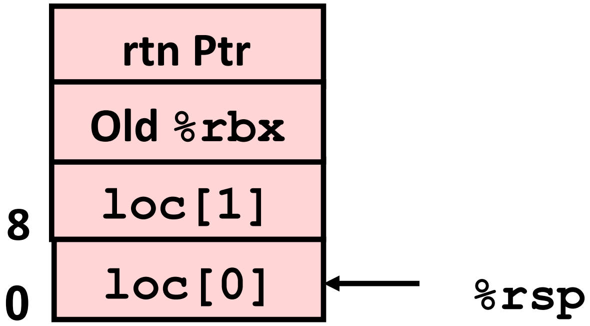


x86-64 Stack Frame Example #3

```
/* Swap a[i] and a[j] */
long swap_ele_l_diff(long a[],
               long i, long j) {
    long *loc[2];
    long b = i & 0x1;
    long diff = a[j] - a[i];
    loc[b] = &a[i];
    loc[1-b] = &a[j];
    swap(loc[0], loc[1]);
    return diff
}
```

```
swap_ele_l_diff:
  pushq   %rbx
  subq    $16, %rsp
  . . .
  call    swap
  . . .
  addq    $16, %rsp
  popq    %rbx
  ret
```

- Have both callee save register & local variable allocation
- Use both push/pop and sub/add



Interesting Features of Stack Frame

- **Allocate entire frame at once**
  - All stack accesses can be relative to `%rsp`
  - Do by:
    - pushing callee save registers (if needed)
    - decrementing stack pointer (if needed)

- **Simple deallocation**
  - Do by:
    - Incrementing stack pointer (possibly)
    - Popping callee save registers (possibly)
  - No base/frame pointer needed

x86-64 Procedure Summary

- **Heavy use of registers**
  - Parameter passing
  - More temporaries since more registers

- **Minimal use of stack**
  - Sometimes none
  - Allocate/deallocate entire block

- **Many tricky optimizations**
  - What kind of stack frame to use
  - Various allocation techniques

Today

- Procedures (x86-64)
- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structures

Basic Data Types

- **Integral**
  - Stored & operated on in general (integer) registers
  - Signed vs. unsigned depends on instructions used

Intel	ASM	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`
quad word	`q`	8	`[unsigned] long int` (x86-64)

- **Floating Point**
  - Stored & operated on in floating point registers

Intel	ASM	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12/16	`long double`

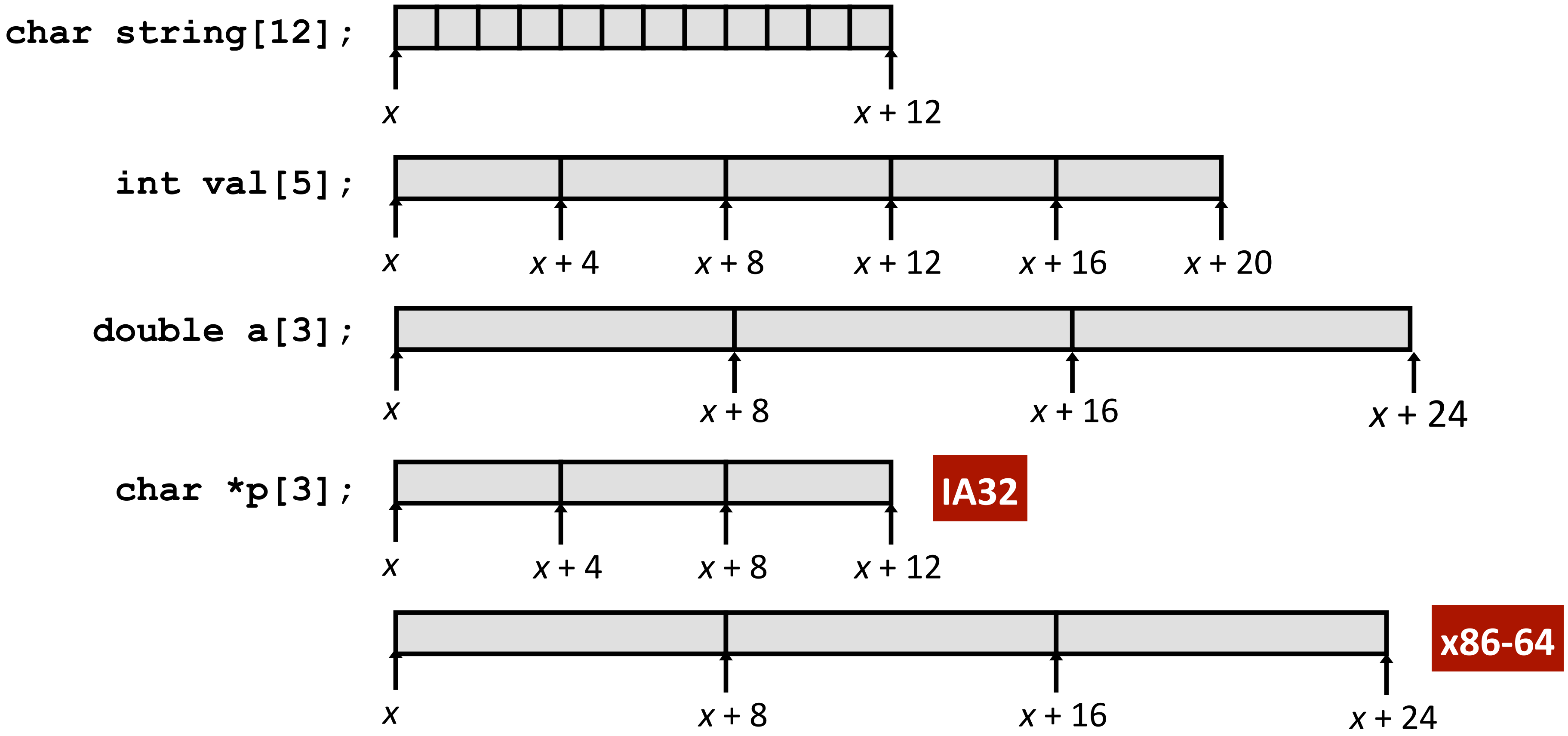
  - Note: Windows Visual C/C++ compiler treats **`long double`** as regular, 8-byte **`double`**. GCC on Windows uses extended precision

Array Allocation

- **Basic Principle**

  T **`A[`***L***`];`**

  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **`sizeof`**`(`*T*`)` bytes



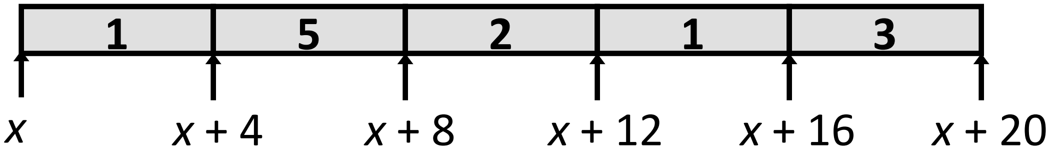
Array Access

Basic Principle

T **A**[*L*];

- Array of data type *T* and length *L*
- Identifier **A** can be used as a pointer to array element 0: Type *T**

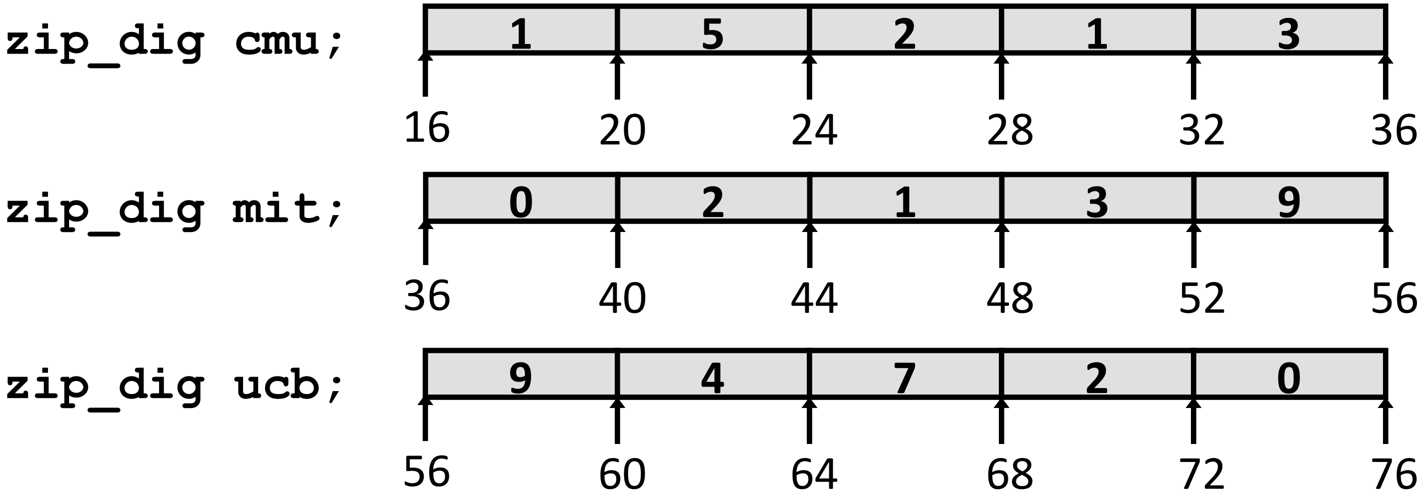
```
int val[5];
```



Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + `*i*	`int *`	*x* + 4 *i*

Array Example

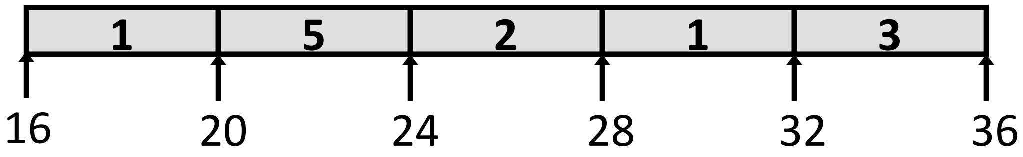
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- **Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"**
- **Example arrays were allocated in successive 20 byte blocks**
  - Not guaranteed to happen in general

Array Accessing Example

```
zip_dig cmu;
```



```
int get_digit
  (zip_dig z, int dig)
{
  return z[dig];
}
```

IA32

```
  # %edx = z
  # %eax = dig
   movl (%edx,%eax,4),%eax   # z[dig]
```

- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

Array Loop Example (IA32)

```
void zincr(zip_dig z) {
  int i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # edx = z
   movl  $0, %eax              #   %eax = i
.L4:                           # loop:
   addl  $1, (%edx,%eax,4)     #   z[i]++
   addl  $1, %eax              #   i++
   cmpl  $5, %eax              #   i:5
   jne   .L4                   #   if !=, goto loop
```

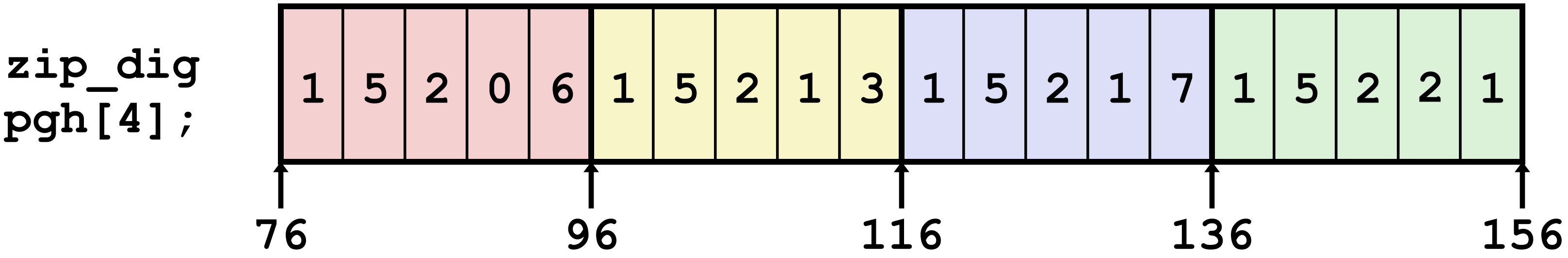
Pointer Loop Example (IA32)

```
void zincr_p(zip_dig z) {
  int *zend = z+ZLEN;
  do {
    (*z)++;
    z++;
  } while (z != zend);
}
```

```
  movl    8(%ebp), %eax    # z
  leal    20(%eax), %edx   # zend
.L9:                       # loop:
  addl    $1, (%eax)       # *z += 1
  addl    $4, %eax         # z++
  cmpl    %eax, %edx       # zend:z
  jne     .L9              # if !=, goto loop
```

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*];

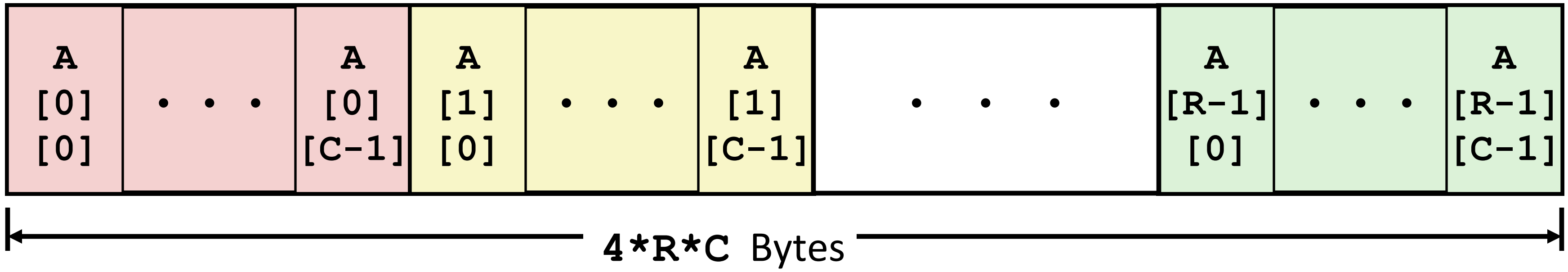
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes

- **Array Size**
  - *R* * *C* * *K* bytes

- **Arrangement**
  - Row-Major Ordering

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

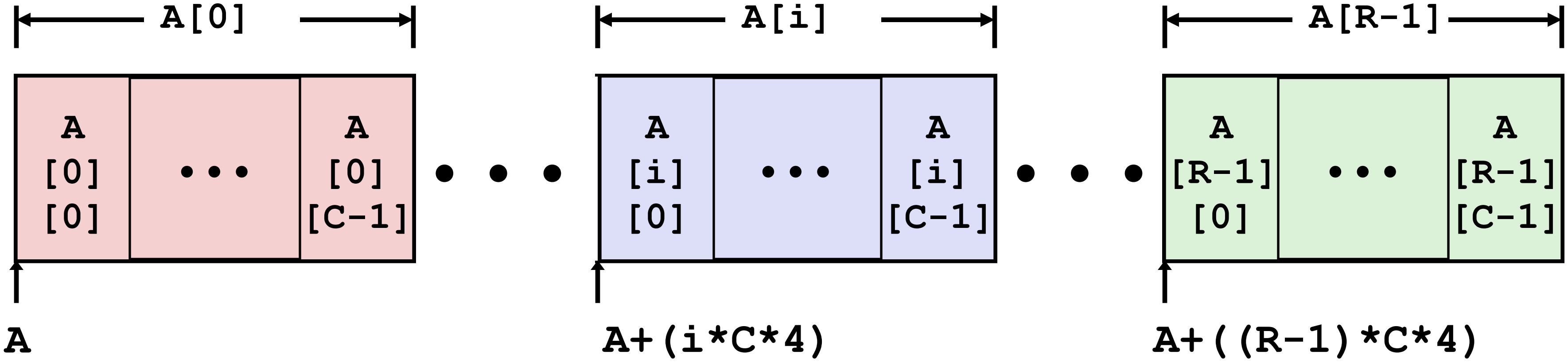
```
int A[R][C];
```



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 }};
```

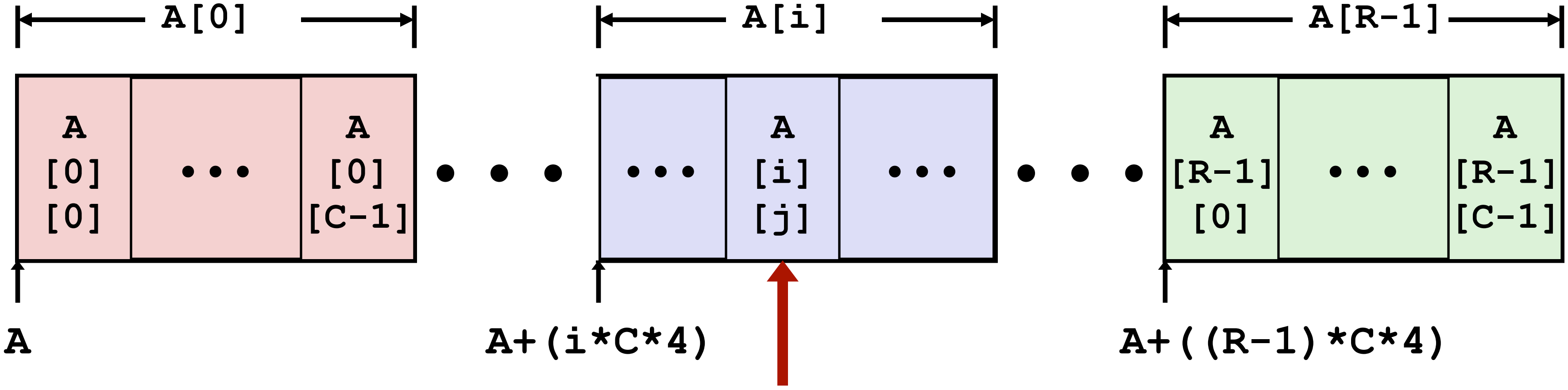
```
  # %eax = index
   leal (%eax,%eax,4),%eax # 5 * index
   leal pgh(,%eax,4),%eax  # pgh + (20 * index)
```

- **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];
```



A+(i*C*4)+(j*4)

Nested Array Element Access Code

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

```
movl   8(%ebp), %eax          # index
leal   (%eax,%eax,4), %eax    # 5*index
addl   12(%ebp), %eax         # 5*index+dig
movl   pgh(,%eax,4), %eax     # offset 4*(5*index+dig)
```

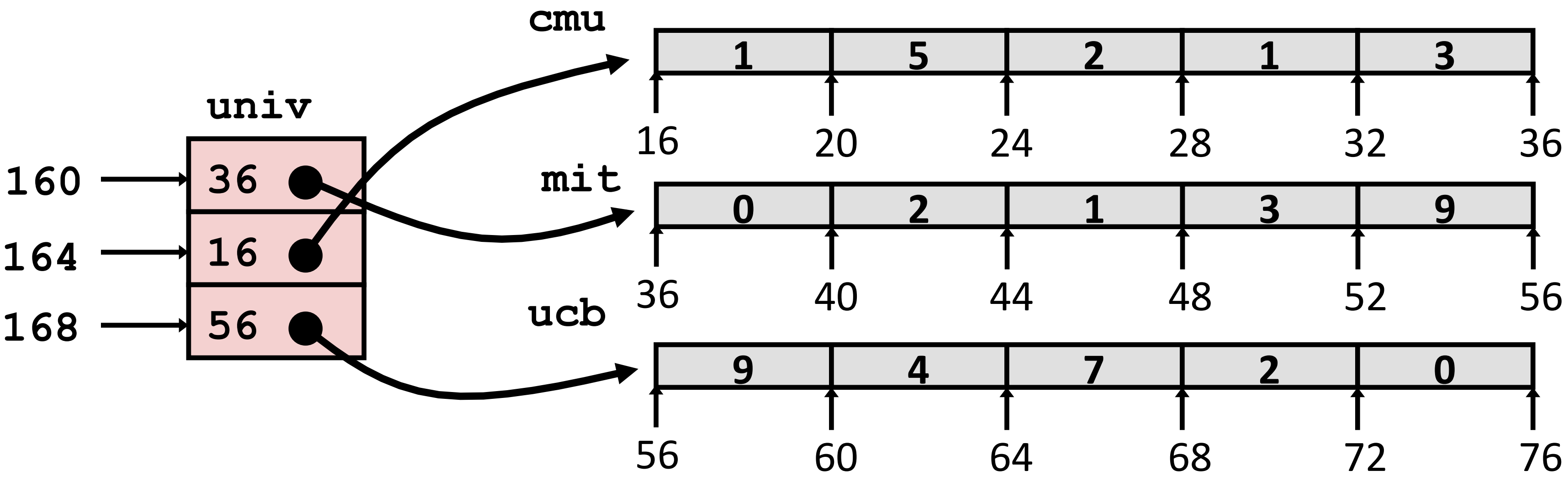
- **Array Elements**
  - **`pgh[index][dig]`** is **`int`**
  - Address: **`pgh + 20*index + 4*dig`**
    - = **`pgh + 4*(5*index + dig)`**
- **IA32 Code**
  - Computes address **`pgh + 4*((index+4*index)+dig)`**

Multi-Level Array Example

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```

- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 4 bytes
- Each pointer points to array of `int`'s



Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

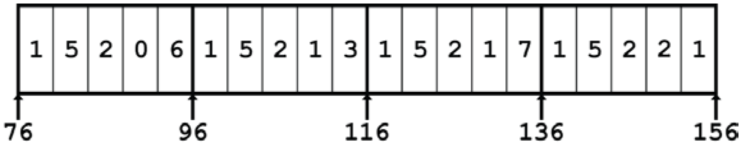
```
  movl  8(%ebp), %eax            # index
  movl  univ(,%eax,4), %edx      # p = univ[index]
  movl  12(%ebp), %eax           # dig
  movl  (%edx,%eax,4), %eax      # p[dig]
```

- **Computation (IA32)**
  - Element access **`Mem[Mem[univ+4*index]+4*dig]`**
  - Must do two memory reads
    - First get pointer to row array
    - Then access element within array

Array Element Accesses

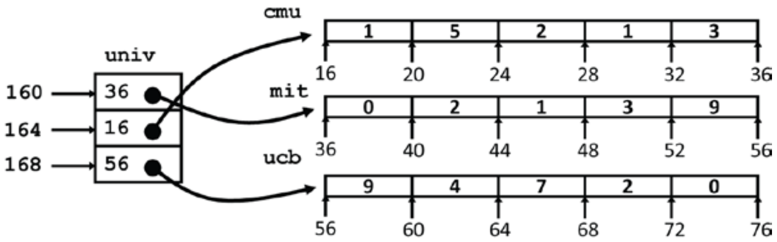
Nested array

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



Multi-level array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```



Accesses looks similar in C, but addresses very different:

`Mem[pgh+20*index+4*dig]`

`Mem[Mem[univ+4*index]+4*dig]`

N X N Matrix Code

- **Fixed dimensions**
  - Know value of N at compile time

```
#define N 16
typedef int fix_matrix[N][N];
/* Get element a[i][j] */
int fix_ele
  (fix_matrix a, int i, int j)
{
  return a[i][j];
}
```

- **Variable dimensions, explicit indexing**
  - Traditional way to implement dynamic arrays

```
#define IDX(n, i, j) ((i)*(n)+(j))
/* Get element a[i][j] */
int vec_ele
 (int n, int *a, int i, int j)
{
  return a[IDX(n,i,j)];
}
```

- **Variable dimensions, implicit indexing**
  - Now supported by gcc

```
/* Get element a[i][j] */
int var_ele
 (int n, int a[n][n], int i, int j)
{
  return a[i][j];
}
```

16 X 16 Matrix Access

- **Array Elements**
  - Address `A + ` *i* * (*C* * *K*) + *j* * *K*
  - C = 16, K = 4

```
/* Get element a[i][j] */
int fix_ele(fix_matrix a, int i, int j) {
  return a[i][j];
}
```

```
   movl   12(%ebp), %edx     # i
   sall   $6, %edx           # i*64
   movl   16(%ebp), %eax     # j
   sall   $2, %eax           # j*4
   addl   8(%ebp), %eax      # a + j*4
   movl   (%eax,%edx), %eax # *(a + j*4 + i*64)
```

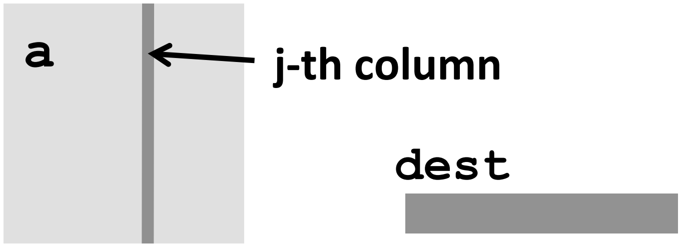
n X n Matrix Access

- **Array Elements**
  - Address **A +** $i * (C * K) + j * K$
  - C = n, K = 4
  - Must perform integer multiplication

```
/* Get element a[i][j] */
int var_ele(int n, int a[n][n], int i, int j) {
  return a[i][j];
}
```

```
   movl   8(%ebp), %eax      # n
   sall   $2, %eax           # n*4
   movl   %eax, %edx         # n*4
   imull  16(%ebp), %edx     # i*n*4
   movl   20(%ebp), %eax     # j
   sall   $2, %eax           # j*4
   addl   12(%ebp), %eax     # a + j*4
   movl   (%eax,%edx), %eax  # *(a + j*4 + i*n*4)
```

Optimizing Fixed Array Access

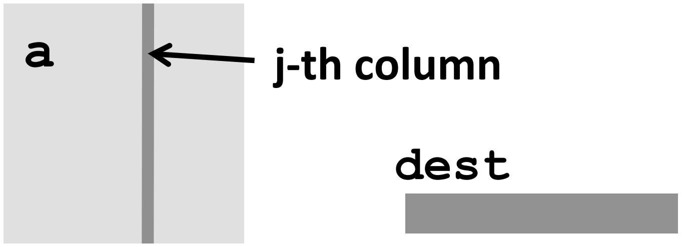


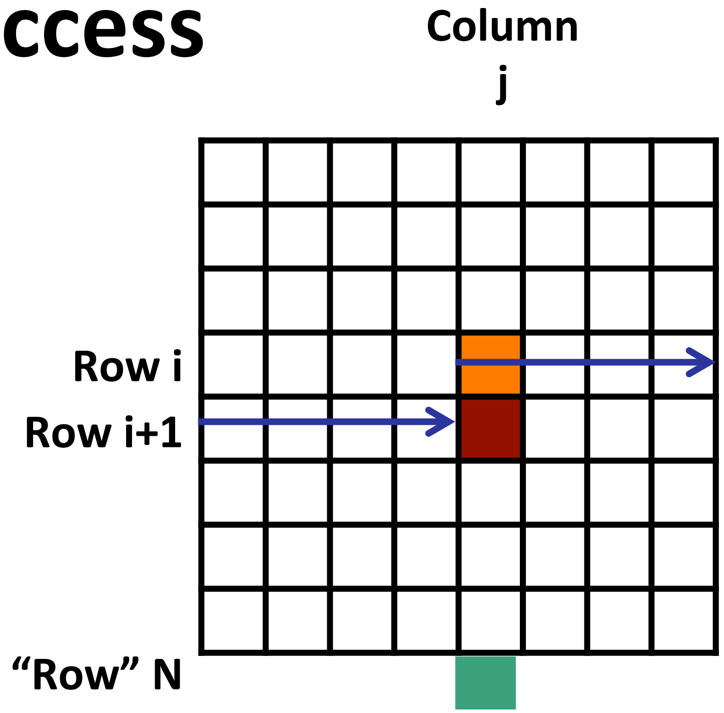
```
#define N 16
typedef int fix_matrix[N][N];
```

```
/* Retrieve column j from array */
void fix_column
  (fix_matrix a, int j, int *dest)
{
  int i;
  for (i = 0; i < N; i++)
    dest[i] = a[i][j];
}
```

- **Computation**
  - Step through all elements in column j
  - Copy to dest
- **Optimization**
  - Retrieving successive elements from single column

Optimizing Fixed Array Access





- **Observations**
  - Elements **a[i][j]** and **a[i+1][j]** are N elements apart
    - Offset = 4*N = 64
  - Stop when hit element **a[N][j]**
    - Offset = 4*N*N = 1024

```
/* Retrieve column j from array */
void fix_column
  (fix_matrix a, int j, int *dest)
{
  int i;
  for (i = 0; i < N; i++)
    dest[i] = a[i][j];
}
```

Optimizing Fixed Array Access

Optimization

- Elements `a[i][j]` and `a[i+1][j]` are N elements apart
- Stop when hit element `a[N][j]`

```
/* Retrieve column j from array */
void fix_column
   (fix_matrix a, int j, int *dest)
{
   int i;
   for (i = 0; i < N; i++)
      dest[i] = a[i][j];
}
```

```
/* Retrieve column j from array */
void fix_column_p(fix_matrix a,
                  int j, int *dest)
{
    int *ap = &a[0][j];
    int *aend = &a[N][j];
    do {
        *dest = *ap;
        dest++;
        ap += N;
    } while (ap != aend);
}
```

Fixed Array Access Code: Set Up

Register	Value
%eax	ap
%edx	dest
%ebx	aend

```
/* Retrieve column j from array */
void fix_column_p(fix_matrix a,
                  int j, int *dest)
{
    int *ap = &a[0][j];
    int *aend = &a[N][j];
    …
}
```

```
movl    12(%ebp), %eax    # j
sall    $2, %eax          # 4*j
addl    8(%ebp), %eax     # a+4*j          == &a[0][j]
movl    16(%ebp), %edx    # dest
leal    1024(%eax), %ebx  # a+4*j+4*16*16 == &a[0][N]
```

Fixed Array Access Code: Loop

Register	Value
`%eax`	`ap`
`%edx`	`dest`
`%ebx`	`aend`

```
do {
    *dest = *ap;
    dest++;
    ap += N;
} while (ap != aend);
```

```
.L9:                       # loop:
  movl    (%eax), %ecx     # t = *ap
  movl    %ecx, (%edx)     # *dest = t
  addl    $64, %eax        # ap += N
  addl    $4, %edx         # dest++
  cmpl    %ebx, %eax       # ap : aend
  jne     .L9              # if != goto loop
```

Optimizing Variable Array Access

```
/* Retrieve column j from array */
void var_column
  (int n, int a[n][n],
   int j, int *dest)
{
  int i;
  for (i = 0; i < n; i++)
    dest[i] = a[i][j];
}
```

- **Observations**
  - Elements **`a[i][j]`** and **`a[i+1][j]`** are n elements apart
    - Offset = 4*n
  - Stop when reach **`dest[N]`**
    - Offset = 4*n

Optimizing Variable Array Access

- **Observations**
  - Elements **a[i][j]** and **a[i+1][j]** are n elements apart
    - Offset = 4*n
  - Stop when reach **dest[N]**
    - Offset = 4*n

```
void var_column
   (int n, int a[n][n],
    int j, int *dest)
{
  int i;
  for (i = 0; i < n; i++)
    dest[i] = a[i][j];
}
```

```
void var_column_p(int n, int a[n][n],
                  int j, int *dest)
{
    int *ap = &a[0][j];
    int *dend = &dest[n];
    while (dest != dend) {
        *dest = *ap;
        dest++;
        ap += n;
    }
}
```

Variable Array Access Code: Set Up

Register	Value
%edx	ap
%eax	dest
%ebx	4*n
%esi	dend

```
void var_column_p(int n, int a[n][n],
                  int j, int *dest)
{
    int *ap = &a[0][j];
    int *dend = &dest[n];
    …
}
```

```
  movl    8(%ebp), %ebx        # n
  movl    20(%ebp), %esi       # dest
  sall    $2, %ebx             # 4*n
  movl    16(%ebp), %edx       # j
  movl    12(%ebp), %eax       # a
  leal    (%eax,%edx,4), %edx  # a+4*j        == &a[0][j]
  movl    %esi, %eax           # dest
  addl    %ebx, %esi           # dest + 4*n   == &dest[n]
```

Variable Array Access Code: Loop

```
while (dest != dend) {
    *dest = *ap;
    dest++;
    ap += n;
}
```

Register	Value
%edx	ap
%eax	dest
%ebx	4*n
%esi	dend

```
.L17:                        # loop:
  movl    (%edx), %ecx #   t = *ap
  movl    %ecx, (%eax) #   *dest = t
  addl    %ebx, %edx   #   ap += n
  addl    $4, %eax     #   dest++
  cmpl    %esi, %eax   #   dest : dend
  jne     .L17         #   if != goto loop
```

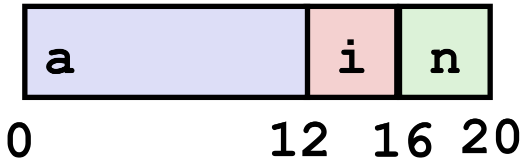
Today

- Procedures (x86-64)
- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access

Structure Allocation

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

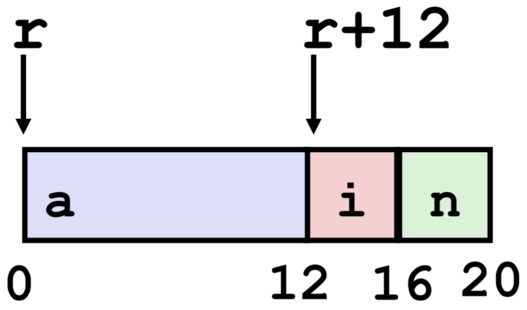
Memory Layout



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

Structure Access

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



- **Accessing Structure Member**
  - Pointer indicates first byte of structure
  - Access elements with offsets

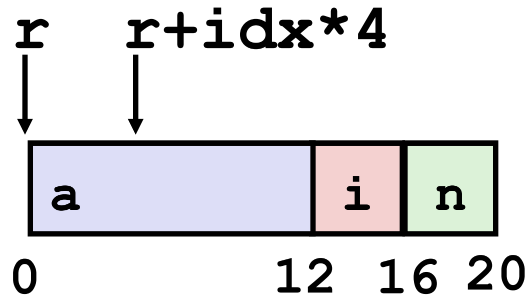
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

IA32 Assembly

```
 # %edx = val
 # %eax = r
movl %edx, 12(%eax)  # Mem[r+12] = val
```

Generating Pointer to Structure Member

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



- **Generating Pointer to Array Element**
  - Offset of each structure member determined at compile time
  - Arguments
    - Mem[%ebp+8]: **r**
    - Mem[%ebp+12]: **idx**

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

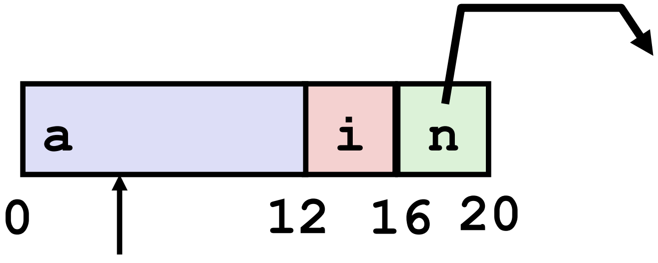
```
movl   12(%ebp), %eax    # Get idx
sall   $2, %eax          # idx*4
addl   8(%ebp), %eax     # r+idx*4
```

Following Linked List

- C Code

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

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->n;
  }
}
```



Element i

Register	Value
%edx	r
%ecx	val

```
.L17:                          # loop:
  movl   12(%edx), %eax        # r->i
  movl   %ecx, (%edx,%eax,4)   # r->a[i] = val
  movl   16(%edx), %edx        # r = r->n
  testl  %edx, %edx            # Test r
  jne    .L17                  # If != 0 goto loop
```

Summary

- **Procedures in x86-64**
  - Stack frame is relative to stack pointer
  - Parameters passed in registers
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access