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

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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
`%rbx`	Callee saved
`%rcx`	Argument #4
`%rdx`	Argument #3
`%rsi`	Argument #2
`%rdi`	Argument #1
`%rsp`	Stack pointer
`%rbp`	Callee saved

`%r8`	Argument #5
`%r9`	Argument #6
`%r10`	Caller saved
`%r11`	Caller Saved
`%r12`	Callee saved
`%r13`	Callee saved
`%r14`	Callee saved
`%r15`	Callee saved

x86-64 Registers

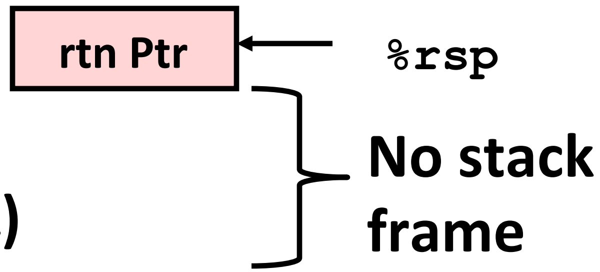
- **Arguments passed to functions via registers**
  - If more than 6 integral parameters, then pass rest on stack
  - These registers can be used as caller-saved as well
- **All references to stack frame via stack pointer**
  - Eliminates need to update **`%ebp/%rbp`**
- **Other Registers**
  - 6 callee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

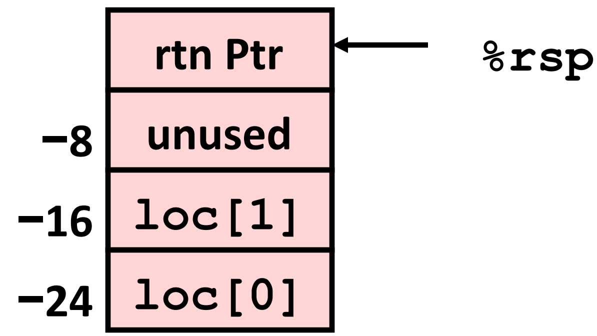


x86-64 Locals in the *Red Zone*

```
/* 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, -24(%rsp)
   movq  (%rsi), %rax
   movq  %rax, -16(%rsp)
   movq  -16(%rsp), %rax
   movq  %rax, (%rdi)
   movq  -24(%rsp), %rax
   movq  %rax, (%rsi)
   ret
```

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



x86-64 NonLeaf without Stack Frame

```
/* Swap a[i] & a[i+1] */
void swap_ele(long a[], int i)
{
    swap(&a[i], &a[i+1]);
}
```

- No values held while swap being invoked
- No callee save registers needed
- `rep` instruction inserted as no-op
  - Based on recommendation from AMD

```
swap_ele:
   movslq %esi,%rsi              # Sign extend i
   leaq   8(%rdi,%rsi,8), %rax  # &a[i+1]
   leaq   (%rdi,%rsi,8), %rdi   # &a[i] (1st arg)
   movq   %rax, %rsi            # (2nd arg)
   call   swap
   rep                           # No-op
   ret
```

x86-64 Stack Frame Example

```
long sum = 0;
/* Swap a[i] & a[i+1] */
void swap_ele_su
  (long a[], int i)
{
    swap(&a[i], &a[i+1]);
    sum += (a[i]*a[i+1]);
}
```

```
swap_ele_su:
    movq    %rbx, -16(%rsp)
    movq    %rbp, -8(%rsp)
    subq    $16, %rsp
    movslq  %esi,%rax
    leaq    8(%rdi,%rax,8), %rbx
    leaq    (%rdi,%rax,8), %rbp
    movq    %rbx, %rsi
    movq    %rbp, %rdi
    call    swap
    movq    (%rbx), %rax
    imulq   (%rbp), %rax
    addq    %rax, sum(%rip)
    movq    (%rsp), %rbx
    movq    8(%rsp), %rbp
    addq    $16, %rsp
    ret
```

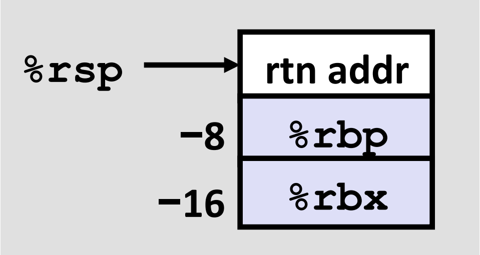
- Keeps values of `&a[i]` and `&a[i+1]` in callee save registers
- Must set up stack frame to save these registers

Understanding x86-64 Stack Frame

```
swap_ele_su:
    movq    %rbx, -16(%rsp)        # Save %rbx
    movq    %rbp, -8(%rsp)         # Save %rbp
    subq    $16, %rsp              # Allocate stack frame
    movslq  %esi,%rax              # Extend i
    leaq    8(%rdi,%rax,8), %rbx   # &a[i+1] (callee save)
    leaq    (%rdi,%rax,8), %rbp    # &a[i]   (callee save)
    movq    %rbx, %rsi             # 2nd argument
    movq    %rbp, %rdi             # 1st argument
    call    swap
    movq    (%rbx), %rax           # Get a[i+1]
    imulq   (%rbp), %rax           # Multiply by a[i]
    addq    %rax, sum(%rip)        # Add to sum
    movq    (%rsp), %rbx           # Restore %rbx
    movq    8(%rsp), %rbp          # Restore %rbp
    addq    $16, %rsp              # Deallocate frame
    ret
```

Understanding x86-64 Stack Frame

```
movq    %rbx, -16(%rsp)        # Save %rbx
movq    %rbp, -8(%rsp)         # Save %rbp
```




```
subq    $16, %rsp              # Allocate stack frame
```

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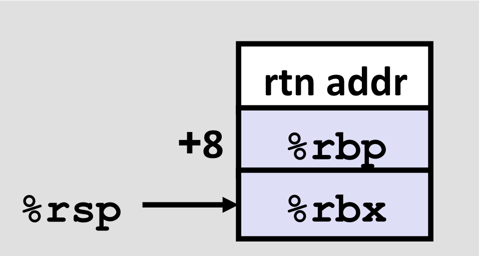



```
movq    (%rsp), %rbx           # Restore %rbx
movq    8(%rsp), %rbp          # Restore %rbp

addq    $16, %rsp              # Deallocate frame
```

Interesting Features of Stack Frame

- **Allocate entire frame at once**
  - All stack accesses can be relative to `%rsp`
  - Do by decrementing stack pointer
  - Can delay allocation, since safe to temporarily use red zone

- **Simple deallocation**
  - Increment stack pointer
  - 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

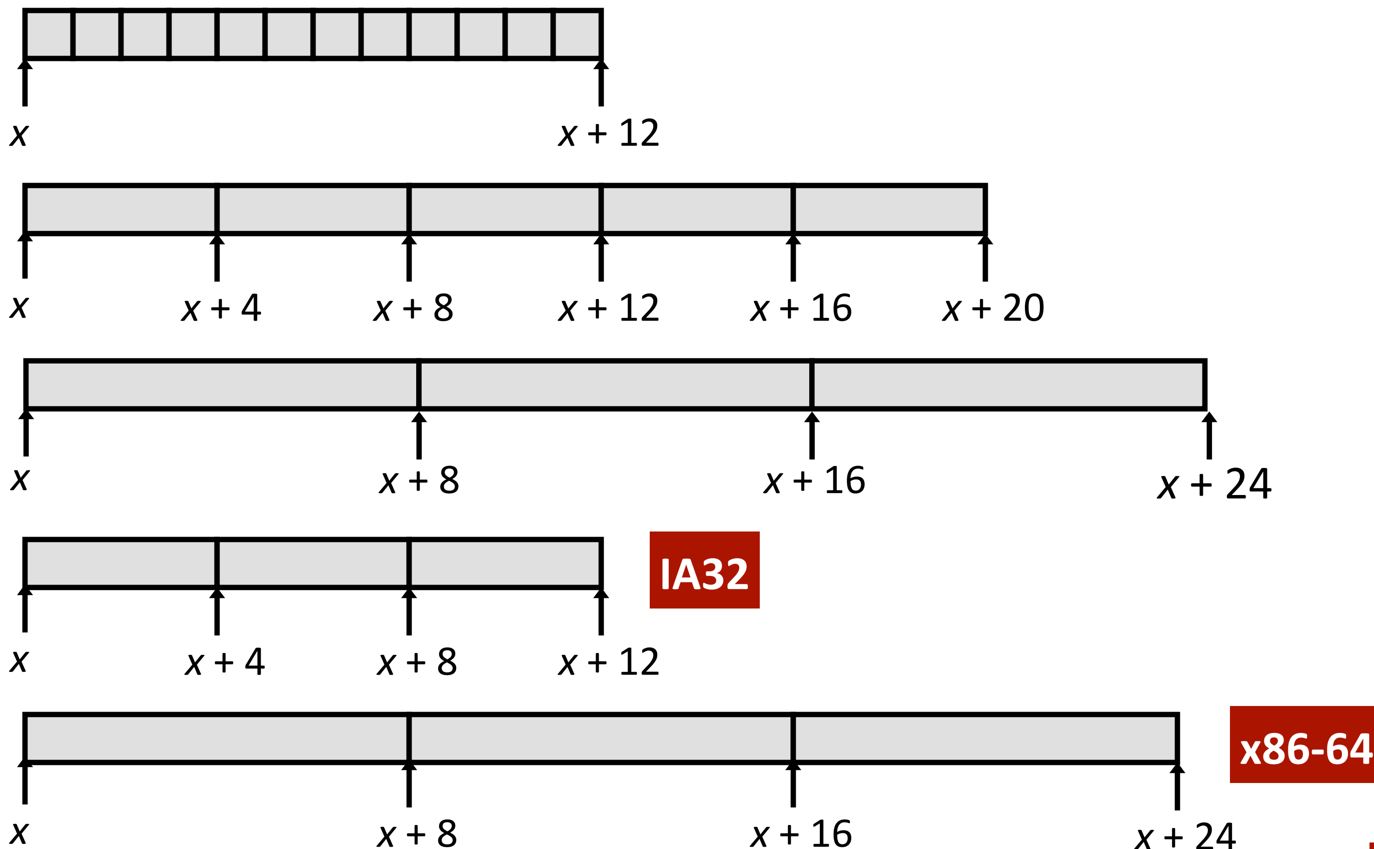
Intel	ASM	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12/16	`long double`

Array Allocation

- **Basic Principle**

  T **A[*L*];**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof**(*T*) bytes

```
char string[12];
int val[5];
double a[3];
char *p[3];
```



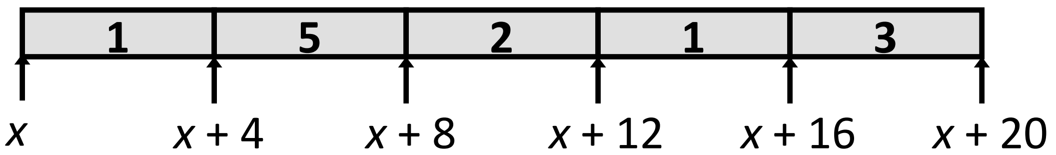
Array Access

■ 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 Access in ASM Examples

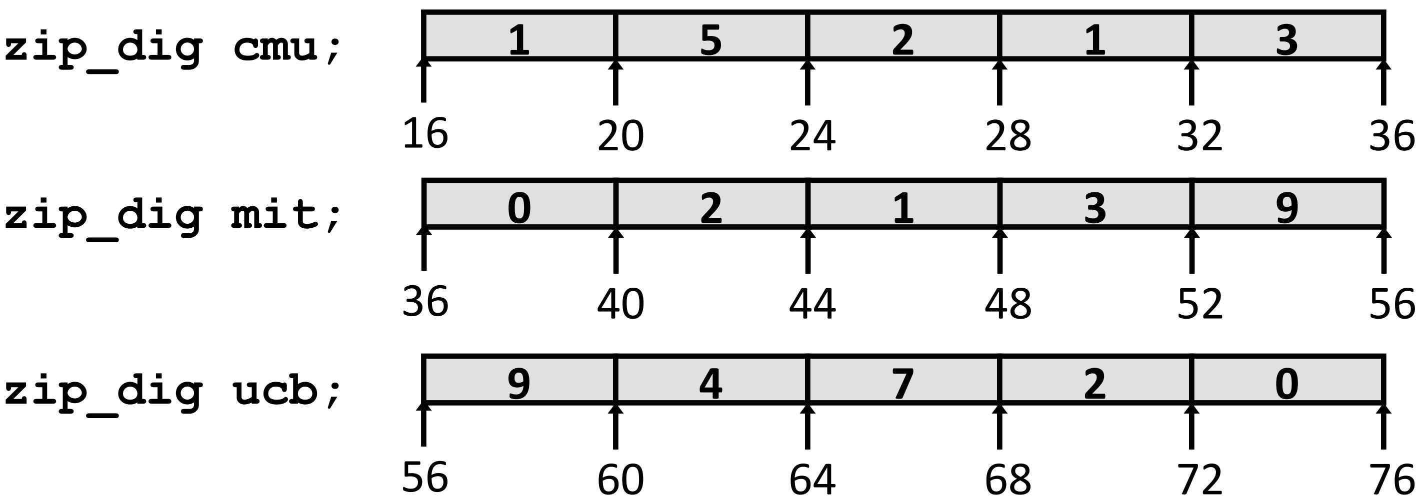
Expression	Type	Value	Assembly Code
`E`	`int *`	X_E	`movl %edx,%eax`
`E[0]`	`int`	$M[\ X_E\ ]$	`movl (%edx),%eax`
`E[i]`	`int`	$M[\ X_E{+}4\ i\ ]$	`movl (%edx,%ecx,4),%eax`
`&E[2]`	`int *`	$X_E + 8$	`leal 8(%edx),%eax`
`E+i-1`	`int *`	$X_E + 4\ i - 4$	`leal -4(%edx,%ecx,4),%eax`
`*(E+i-3)`	`int`	$M[\ X_E{+}\ 4\ i - 12\ ]$	`movl -12(%edx,%ecx,4),%eax`
`&E[i]-E`	`int`	i	`movl %ecx,%eax`

X_E Address
M [ ] Value stored in address

Remember that A[i] is the same as *(A+i)

Array Example

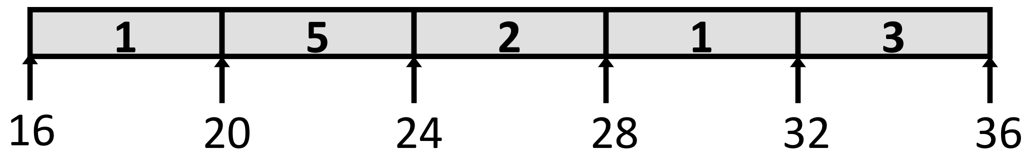
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

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);
}
```

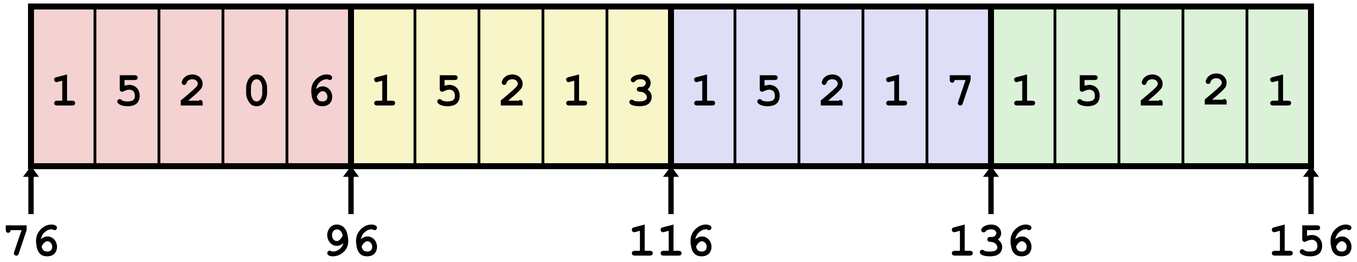
```
void zincr_v(zip_dig z) {
  void *vz = z;
  int i = 0;
  do {
    (*((int *) (vz+i)))++;
    i += ISIZE;
  } while (i != ISIZE*ZLEN);
}
```

```
  # edx = z = vz
  movl  $0, %eax              #   i = 0
.L8:                          # loop:
  addl  $1, (%edx,%eax)       #   Increment vz+i
  addl  $4, %eax              #   i +=  4
  cmpl  $20, %eax             #   Compare i:20
  jne   .L8                   #   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];
```



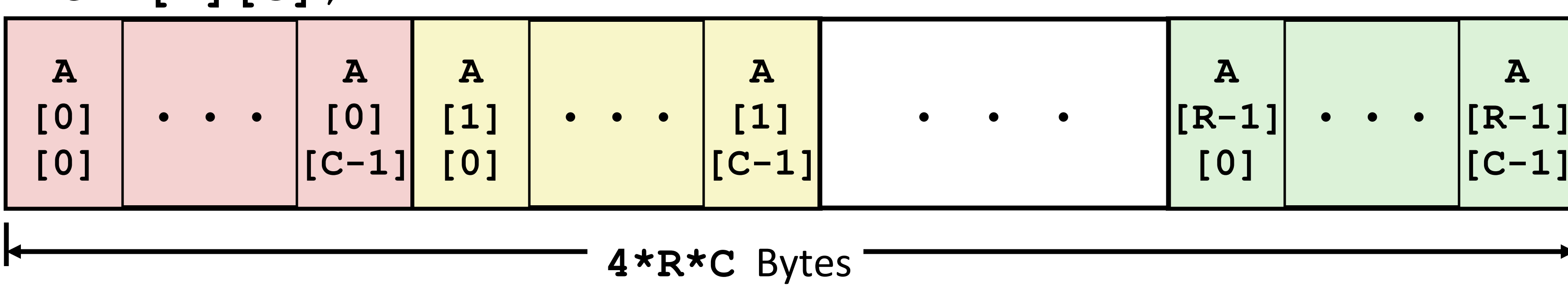
- “`zip_dig pgh[4]`” equivalent to “`int pgh[4][5]`”
  - Variable **`pgh`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**’s, allocated contiguously
- “Row-Major” ordering of all elements guaranteed

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

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

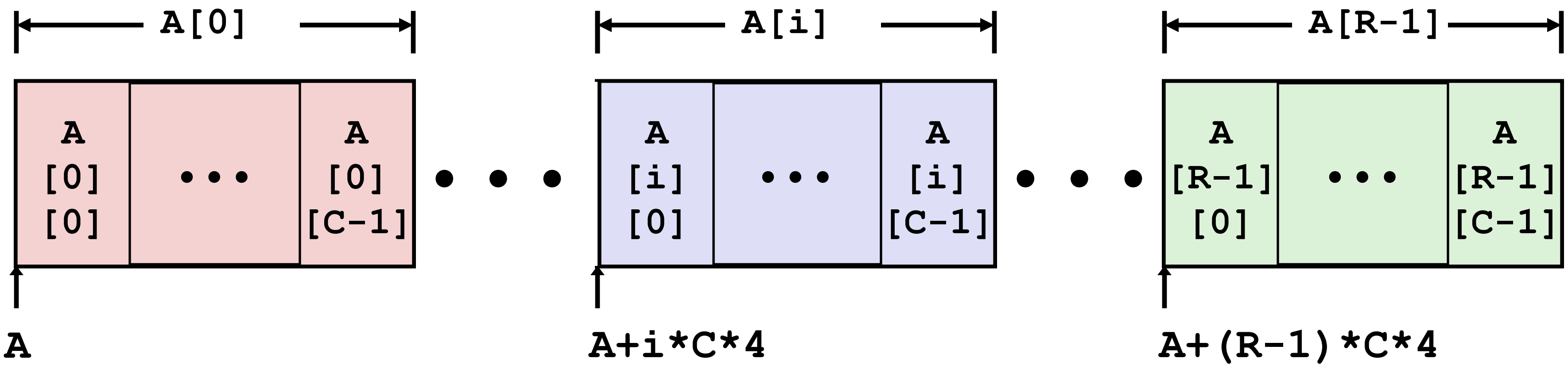
```
int A[R][C];
```



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 }};
```

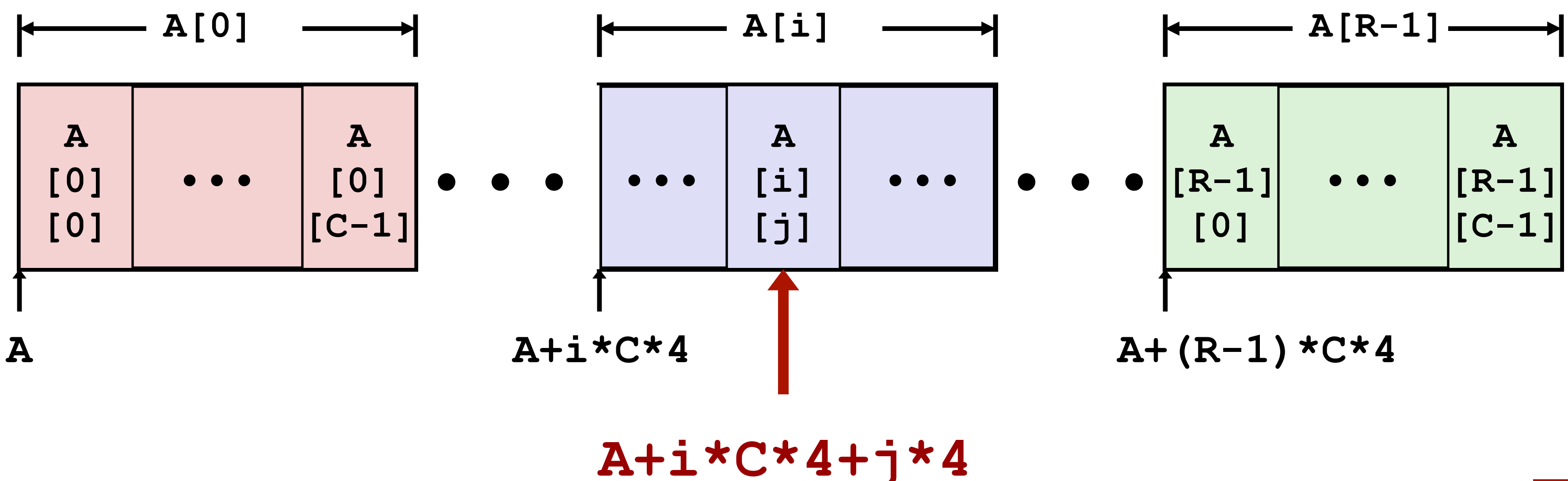
```
  # %eax = index
   leal (%eax,%eax,4),%eax # 5 * index
   leal pgh(,%eax,4),%eax  # pgh + (20 * index)
```

- **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];
```



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)
```

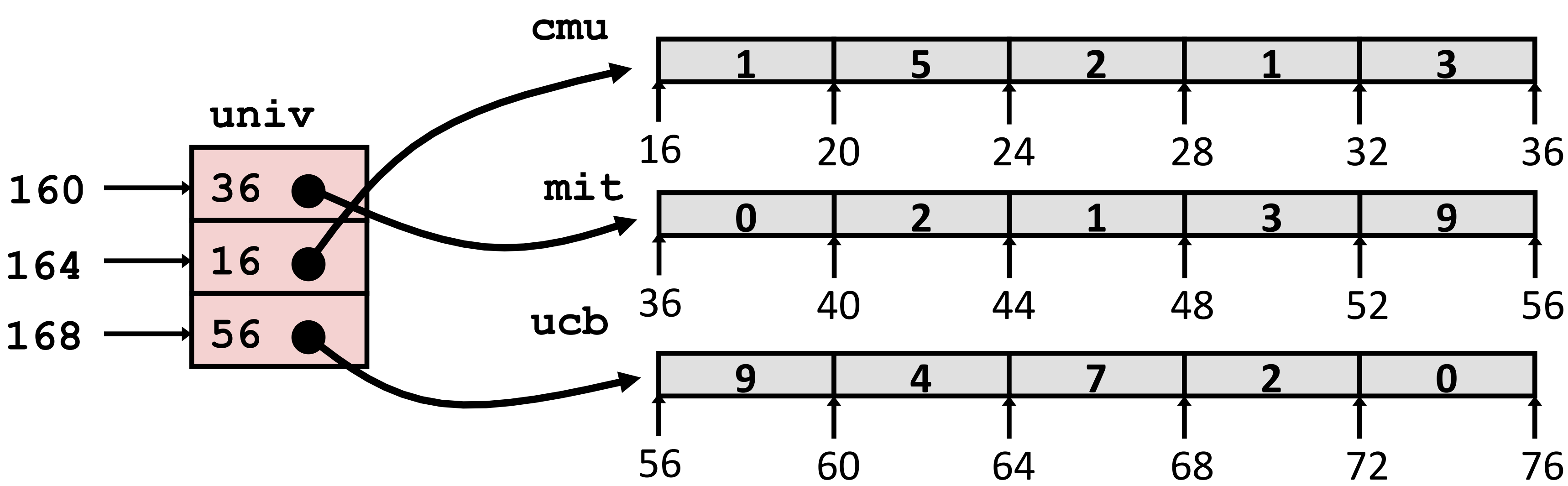
- **Array Elements**
  - `pgh[index][dig]` is `int`
  - Address: `pgh + 20*index + 4*dig`
    - `= pgh + 4*(5*index + dig)`
- **IA32 Code**
  - Computes address `pgh + 4*((index+4*index)+dig)`

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];
}
```

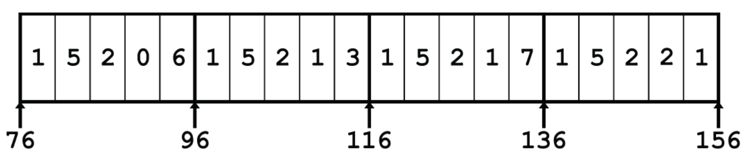
```
  movl   8(%ebp), %eax              # index
  movl   univ(,%eax,4), %edx        # p = univ[index]
  movl   12(%ebp), %eax             # dig
  movl   (%edx,%eax,4), %eax        # p[dig]
```

- **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

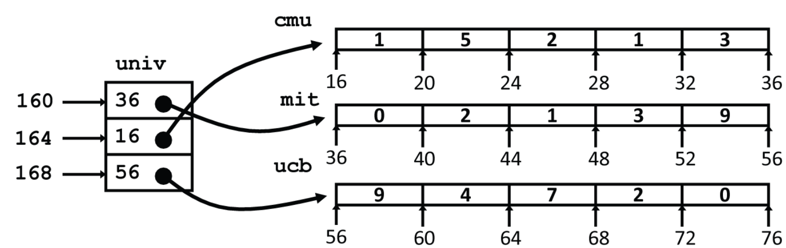
Nested array

```
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
- **Variable dimensions, explicit indexing**
  - Traditional way to implement dynamic arrays
- **Variable dimensions, implicit indexing**
  - Now supported by gcc

```
#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];
}
```

```
#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)];
}
```

```
/* 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)
```

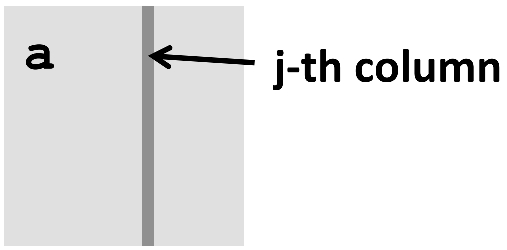
n X n Matrix Access

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

```
/* 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
- **Optimization**
  - Retrieving successive elements from single column

Optimizing Fixed Array Access

- **Optimization**
  - Compute ajp = &a[i][j]
    - Initially = a + 4*j
    - Increment by 4*N

Register	Value
`%ecx`	`ajp`
`%ebx`	`dest`
`%edx`	`i`

```
/* 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];
}
```

```
.L8:                              # loop:
   movl  (%ecx), %eax             #   Read *ajp
   movl  %eax, (%ebx,%edx,4)      #   Save in dest[i]
   addl  $1, %edx                 #   i++
   addl  $64, %ecx                #   ajp += 4*N
   cmpl  $16, %edx                #   i:N
   jne   .L8                      #   if !=, goto loop
```

Optimizing Variable Array Access

- Compute ajp = &a[i][j]
  - Initially = a + 4*j
  - Increment by 4*n

Register	Value
%ecx	ajp
%edi	dest
%edx	i
%ebx	4*n
%esi	n

```
/* 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];
}
```

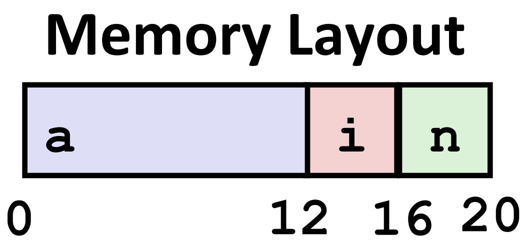
```
.L18:                          # loop:
   movl   (%ecx), %eax         #    Read *ajp
   movl   %eax, (%edi,%edx,4)  #    Save in dest[i]
   addl   $1, %edx             #    i++
   addl   $ebx, %ecx           #    ajp += 4*n
   cmpl   $edx, %esi           #    n:i
   jg     .L18                 #    if >, goto loop
```

Today

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

Structure Allocation

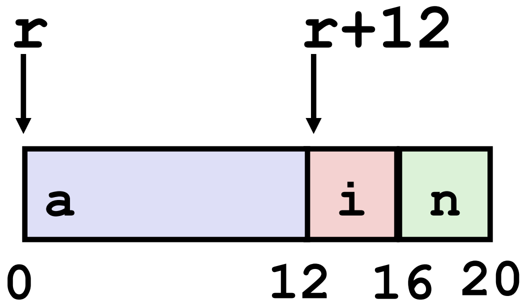
```
struct rec {
  int a[3];
  int i;
  struct rec *n;
};
```



- **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

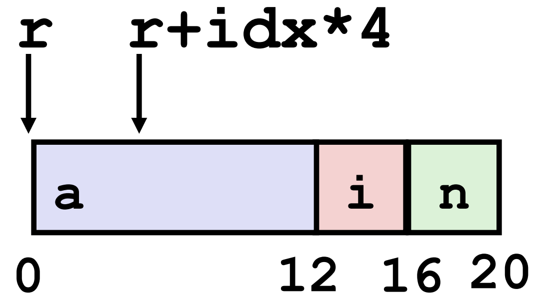
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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];
}
```

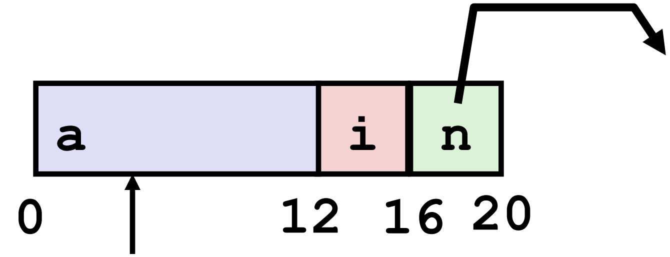
```
movl   12(%ebp), %eax    # Get idx
sall   $2, %eax          # idx*4
addl   8(%ebp), %eax     # r+idx*4
```

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

Following Linked List

- C Code

```
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