Introduction to Computer Systems

15-213/18-243, fall 2009
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Last Time

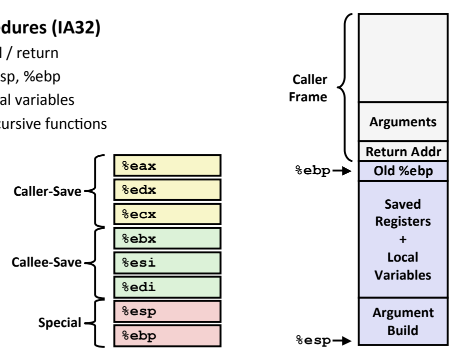
- **For loops**
  - for loop → while loop → do-while loop → goto version
  - for loop → while loop → goto "jump to middle" version
- **Switch statements**
  - Jump tables: `jmp *.L62(,%edx,4)`
  - Decision trees (not shown)

Jump table

```
.section .rodata
  .align 4
.L62:
  .long   .L61  # x = 0
  .long   .L56  # x = 1
  .long   .L57  # x = 2
  .long   .L58  # x = 3
  .long   .L61  # x = 4
  .long   .L60  # x = 5
  .long   .L60  # x = 6
```

Last Time

- **Procedures (IA32)**
  - call / return
  - %esp, %ebp
  - local variables
  - recursive functions



Today

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

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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

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x86-64 Integer Registers

%rax	Return value	%r8	Argument #5
%rbx	Callee saved	%r9	Argument #6
%rcx	Argument #4	%r10	Callee saved
%rdx	Argument #3	%r11	Used for linking
%rsi	Argument #2	%r12	C: 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+1 callee saved
  - 2 or 3 have special uses

x86-64 Long Swap

```
void swap(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

	rtn Ptr	← `%rsp`
−8	unused	
−16	`loc[1]`	
−24	`loc[0]`	

x86-64 NonLeaf without Stack Frame

```
long scount = 0;

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

- **No values held while swap being invoked**
- **No callee save registers needed**

```
swap_ele_se:
  movslq %esi,%rsi             # Sign extend i
  leaq   (%rdi,%rsi,8), %rdi   # &a[i]
  leaq   8(%rdi), %rsi         # &a[i+1]
  call   swap                  # swap()
  incq   scount(%rip)          # scount++;
  ret
```


x86-64 Call using Jump

```
long scount = 0;

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

```
swap_ele:
  movslq %esi,%rsi
  leaq   (%rdi,%rsi,8), %rdi
  leaq   8(%rdi), %rsi
  jmp    swap
```

Will disappear Blackboard?

x86-64 Call using Jump

```
long scount = 0;

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

- **When swap executes `ret`, it will return from `swap_ele`**
- **Possible since swap is a "tail call" (no instructions afterwards)**

```
swap_ele:
  movslq %esi,%rsi             # Sign extend i
  leaq   (%rdi,%rsi,8), %rdi   # &a[i]
  leaq   8(%rdi), %rsi         # &a[i+1]
  jmp    swap                  # swap()
```

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];
}
```

```
swap_ele_su:
  movq    %rbx, -16(%rsp)
  movslq  %esi,%rbx
  movq    %r12, -8(%rsp)
  movq    %rdi, %r12
  leaq    (%rdi,%rbx,8), %rdi
  subq    $16, %rsp
  leaq    8(%rdi), %rsi
  call    swap
  movq    (%r12,%rbx,8), %rax
  addq    %rax, sum(%rip)
  movq    (%rsp), %rbx
  movq    8(%rsp), %r12
  addq    $16, %rsp
  ret
```

- Keeps values of a and i in callee save registers
- Must set up stack frame to save these registers

Blackboard?

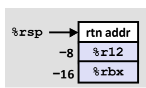
Understanding x86-64 Stack Frame

```
swap_ele_su:
  movq    %rbx, -16(%rsp)        # Save %rbx
  movslq  %esi,%rbx              # Extend & save i
  movq    %r12, -8(%rsp)         # Save %r12
  movq    %rdi, %r12             # Save a
  leaq    (%rdi,%rbx,8), %rdi    # &a[i]
  subq    $16, %rsp              # Allocate stack frame
  leaq    8(%rdi), %rsi          #     &a[i+1]
  call    swap                   # swap()
  movq    (%r12,%rbx,8), %rax    # a[i]
  addq    %rax, sum(%rip)        # sum += a[i]
  movq    (%rsp), %rbx           # Restore %rbx
  movq    8(%rsp), %r12          # Restore %r12
  addq    $16, %rsp              # Deallocate stack frame
  ret
```

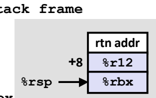

Understanding x86-64 Stack Frame

```
swap_ele_su:
  movq    %rbx, -16(%rsp)        # Save %rbx

  movq    %r12, -8(%rsp)         # Save %r12
```




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




```
  movq    (%rsp), %rbx           # Restore %rbx
  movq    8(%rsp), %r12          # Restore %r12
  addq    $16, %rsp              # Deallocate stack 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
  - Calling with jump
  - 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

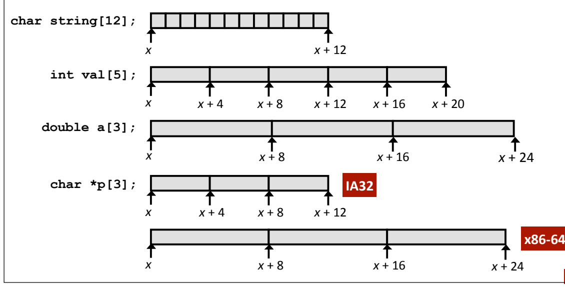
Intel	GAS	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`
quad word	`q`	8	`[unsigned] long int` (x86-64)

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

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

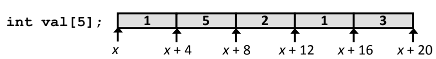
Array Allocation

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



Array Access

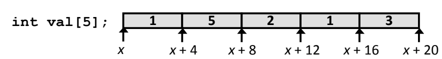
- **Basic Principle**
  T `A[`*L*`];`
  - Array of data type *T* and length *L*
  - Identifier `A` can be used as a pointer to array element 0: Type *T**



■ Reference	Type	Value
`val[4]`		
`val`		
`val+1`	Will disappear	
`&val[2]`	Blackboard?	
`val[5]`		
`*(val+1)`		
`val +` *i*		

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**

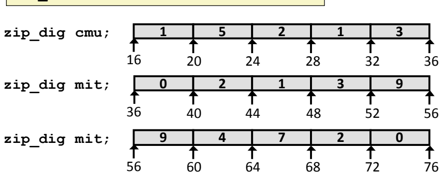


■ Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val +` *i*	`int *`	*x* + 4 *i*

Array Example

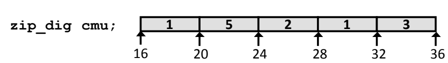
```
typedef int zip_dig[5];

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



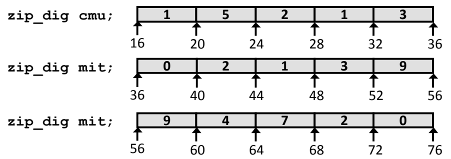

```
int get_digit
  (zip_dig z, int dig)
{
  return z[dig];
}
```

IA32

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

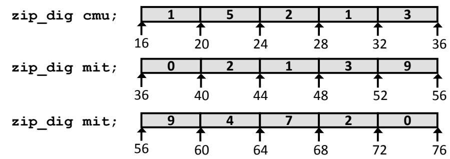
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

Referencing Examples



Reference	Address	Value	Guaranteed?
`mit[3]`	Will disappear Blackboard?		
`mit[5]`			
`mit[-1]`			
`cmu[15]`			

Referencing Examples



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

Array Loop Example

- **Original**

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- **Transformed**
  - As generated by GCC
  - Eliminate loop variable `i`
  - Convert array code to pointer code
  - Express in do-while form (no test at entrance)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```


Array Loop Implementation (IA32)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %ecx = z
  xorl %eax,%eax
  leal 16(%ecx),%ebx
.L59:
  leal (%eax,%eax,4),%edx
  movl (%ecx),%eax
  addl $4,%ecx
  leal (%eax,%edx,2),%eax
  cmpl %ebx,%ecx
  jle .L59
```

Will disappear Blackboard?

Array Loop Implementation (IA32)

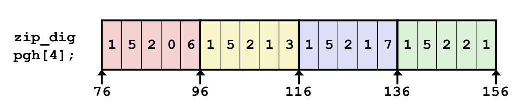
- **Registers**
  `%ecx z`
  `%eax zi`
  `%ebx zend`
- **Computations**
  - `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
  - `z++` increments by 4

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %ecx = z
  xorl %eax,%eax              # zi = 0
  leal 16(%ecx),%ebx          # zend  = z+4
.L59:
  leal (%eax,%eax,4),%edx     # 5*zi
  movl (%ecx),%eax            # *z
  addl $4,%ecx                # z++
  leal (%eax,%edx,2),%eax     # zi = *z + 2*(5*zi)
  cmpl %ebx,%ecx              # z : zend
  jle .L59                    # if <= goto loop
```


Nested Array Example

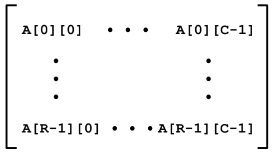
```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



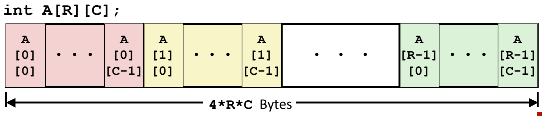
- **“`zip_dig pgh[4]`” equivalent to “`int pgh[4][5]`”**
  - Variable `pgh`: array of 4 elements, allocated contiguously
  - Each element is an array of 5 `int`’s, allocated contiguously
- **“Row-Major” ordering of all elements guaranteed**

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



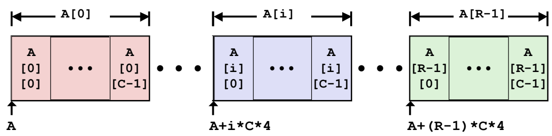
`int A[R][C];`



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 }};
```

- **What data type is `pgh[index]`?**
- **What is its starting address?**

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

Will disappear Blackboard?

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 }};
```

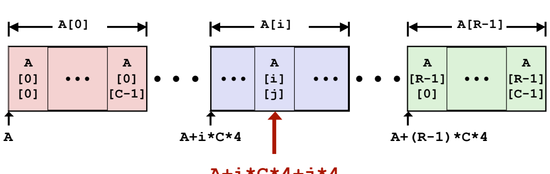
```
 # %eax = index
  leal (%eax,%eax,4),%eax # 5 * index
  leal pgh(,%eax,4),%eax  # pgh + (20 * index)
```

- **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

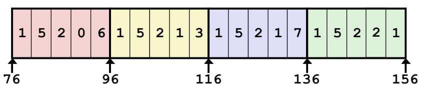
```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

```
 # %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

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



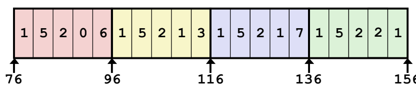
- **Reference** **Address** **Value** **Guaranteed?**

```
pgh[3][3]
pgh[2][5]
pgh[2][-1]
pgh[4][-1]
pgh[0][19]
pgh[0][-1]
```

Will disappear

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]`	`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

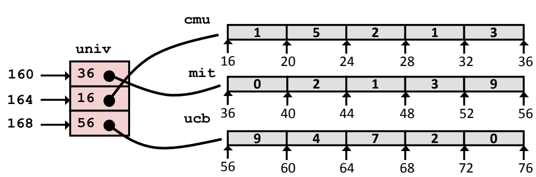
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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];
}
```

```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx
  movl univ(%edx),%edx
  movl (%edx,%eax,4),%eax
```

Will disappear
Blackboard?

Element Access in Multi-Level Array

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

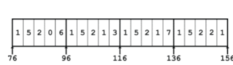
```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx     # 4*index
  movl univ(%edx),%edx     # Mem[univ+4*index]
  movl (%edx,%eax,4),%eax  # Mem[...+4*dig]
```

- **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

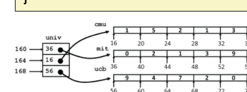
Nested array

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



Multi-level array

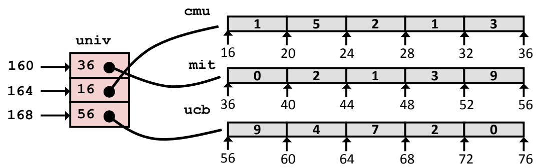
```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```



Access looks similar, but element:

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

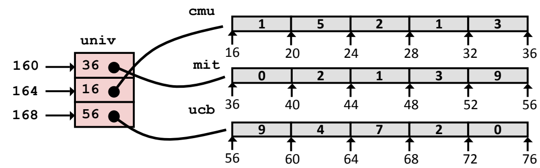
Strange Referencing Examples



- **Reference** | **Address** | **Value** | **Guaranteed?**

Reference	Address	Value	Guaranteed?
`univ[2][3]`	Will disappear		
`univ[1][5]`			
`univ[2][-1]`			
`univ[3][-1]`			
`univ[1][12]`			

Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`56+4*3 = 68`	`2`	Yes
`univ[1][5]`	`16+4*5 = 36`	`0`	No
`univ[2][-1]`	`56+4*-1 = 52`	`9`	No
`univ[3][-1]`	`??`	`??`	No
`univ[1][12]`	`16+4*12 = 64`	`7`	No

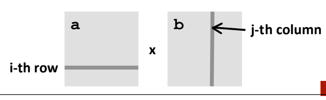
- Code does not do any bounds checking
- Ordering of elements in different arrays not guaranteed

Using Nested Arrays

- **Strengths**
  - C compiler handles doubly subscripted arrays
  - Generates very efficient code
  - Avoids multiply in index computation
- **Limitation**
  - Only works for fixed array size

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

```
/* Compute element i,k of
   fixed matrix product */
int fix_prod_ele
(fix_matrix a, fix_matrix b,
 int i, int k)
{
  int j;
  int result = 0;
  for (j = 0; j < N; j++)
    result += a[i][j]*b[j][k];
  return result;
}
```



Dynamic Nested Arrays

- **Strength**
  - Can create matrix of any size
- **Programming**
  - Must do index computation explicitly
- **Performance**
  - Accessing single element costly
  - Must do multiplication

```
int * new_var_matrix(int n)
{
  return (int *)
    calloc(sizeof(int), n*n);
}
```

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

```
movl 12(%ebp),%eax      # i
movl 8(%ebp),%edx       # a
imull 20(%ebp),%eax     # n*i
addl 16(%ebp),%eax      # n*i+j
movl (%edx,%eax,4),%eax # Mem[a+4*(i*n+j)]
```


Dynamic Array Multiplication

- **Without Optimizations**
  - Multiplies: 3
    - 2 for subscripts
    - 1 for data
  - Adds: 4
    - 2 for array indexing
    - 1 for loop index
    - 1 for data

```
/* Compute element i,k of
   variable matrix product */
int var_prod_ele
  (int *a, int *b,
   int i, int k, int n)
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n+j] * b[j*n+k];
  return result;
}
```


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;
}
```

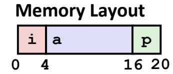
Today

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

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**

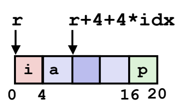
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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];
}
```

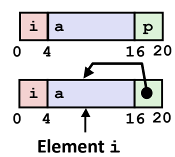
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax    # 4*idx
leal 4(%eax,%edx),%eax  # r+4*idx+4
```


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
```


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**