15-213

"The course that gives CMU its Zip!"

Structured Data I: Homogenous Data February 8, 2001

Topics

- **Arrays**
  - Single
  - Nested
- **Pointers**
  - Multilevel Arrays
- **Optimized Array Code**

Basic Data Types

Integral

- Stored & operated on in general 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

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	long double

Pointer

- Stored & operated on in general registers

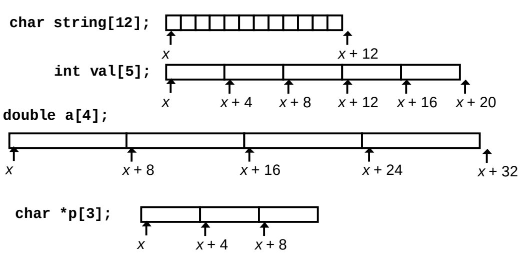
Intel	GAS	Bytes	C
Double	l	8	char *

Array Allocation

Basic Principle

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

- **Array named A of data type *T* with *L* elements**
- **Contiguously allocated region of *L* * sizeof(*T*) bytes**

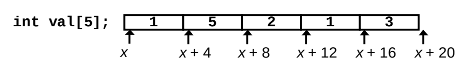


Array Access

Basic Principle

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

- Array named A of data type *T* and length *L*
- Identifier A can be used as a pointer to starting element of the array



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 };
```

```
zip_dig cmu;  | 1 | 5 | 2 | 1 | 3 |
              16  20  24  28  32  36
zip_dig mit;  | 0 | 2 | 1 | 3 | 9 |
              36  40  44  48  52  56
zip_dig ucb;  | 9 | 4 | 7 | 2 | 0 |
              56  60  64  68  72  76
```

Notes

- **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

Computation

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

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

Memory Reference Code

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


Referencing Examples

```
zip_dig cmu;  | 1 | 5 | 2 | 1 | 3 |
              16  20  24  28  32  36
zip_dig mit;  | 0 | 2 | 1 | 3 | 9 |
              36  40  44  48  52  56
zip_dig ucb;  | 9 | 4 | 7 | 2 | 0 |
              56  60  64  68  72  76
```

Code Does Not Do Any Bounds Checking!

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

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

Array Loop Example

Original Source

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

Transformed Version

- **Eliminate loop variable `i`**
- **Convert array code to pointer code**
- **Express in do-while form**
  - No need to 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

Registers

```
%ecx  z
%eax  zi
%ebx  zend
```

Computations

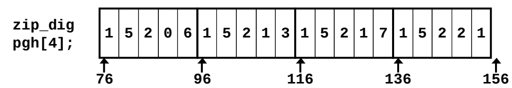
- `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
- `z++` increments by 4

```
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 }};
```



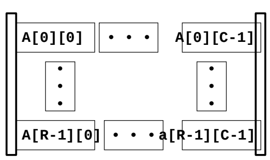
- **Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"**
  - Variable **pgh** denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 **int**'s
    - » Allocated contiguously
- **"Row-Major" ordering of all elements guaranteed**

Nested Array Allocation

Declaration

T **A[***R***][***C***];**

- **Array of data type** *T*
- *R* **rows**
- *C* **columns**
- **Type** *T* **element requires** *K* **bytes**



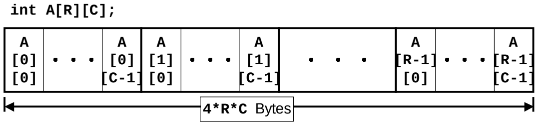
Array Size

- *R* * *C* * *K* **bytes**

Arrangement

- Row-Major Ordering

`int A[R][C];`

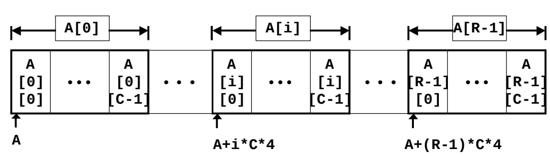


Nested Array Row Access

Row Vectors

- **`A[i]` is array of** *C* **elements**
- **Each element of type** *T*
- **Starting address A +** *i* * *C* * *K*

`int A[R][C];`



Nested Array Row Access Code

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

Row Vector

- `pgh[index]` is array of 5 `int`'s
- Starting address `pgh+20*index`

Code

- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

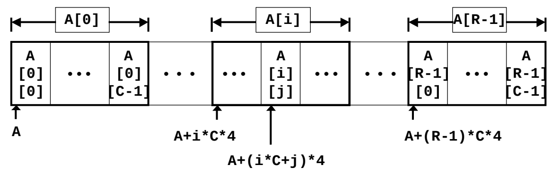

Nested Array Element Access

Array Elements

- `A[i][j]` is element of type *T*
- Address `A +` (*i* * *C* + *j*) * *K*

A
[i]
[j]

`int A[R][C];`



Nested Array Element Access Code

Array Elements

- `pgh[index][dig]` is `int`
- Address:
  `pgh + 20*index + 4*dig`

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

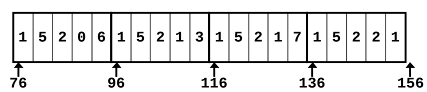
Code

- Computes address
  `pgh + 4*dig + 4*(index+4*index)`
- `movl` performs memory reference

```
# %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)
```


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

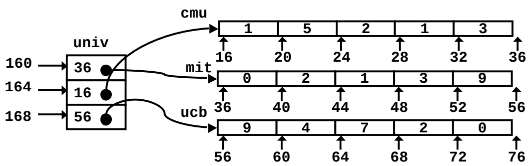
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

Multi-Level Array Example

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

```
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};
```



Referencing "Row" in Multi-Level Array

Row Vector

- `univ[index]` is pointer to array of `int`'s
- Starting address `Mem[univ+4*index]`

```
int* get_univ_zip(int index)
{
  return univ[index];
}
```

Code

- Computes address within `univ`
- Reads pointer from memory and returns it

```
# %edx = index
leal 0(,%edx,4),%eax   # 4*index
movl univ(%eax),%eax   # *(univ+4*index)
```


Accessing Element in Multi-Level Array

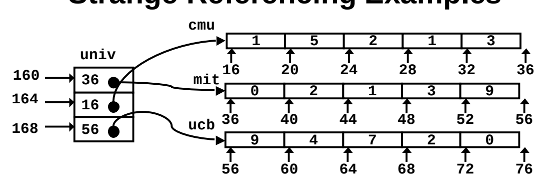
Computation

- 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

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


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

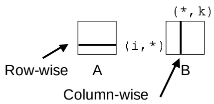
- C compiler handles doubly subscripted arrays
- Generates very efficient code
  - Avoids multiply in index computation

Limitation

- Only works if have 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 arbitrary 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];
}
```

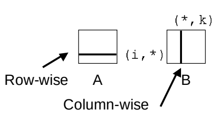
```
movl 12(%ebp),%eax      # i
movl 8(%ebp),%edx       # a
imull 20(%ebp),%eax     # n*i
addl 16(%ebp),%eax      # n*i+j
movl (%edx,%eax,4),%eax # Mem[a+4*(i*n+j)]
```


Dynamic Array Multiplication

Without Optimizations

- Multiplies
  - 2 for subscripts
  - 1 for data
- Adds
  - 4 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

Performance

- 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;
}
```

Dynamic Array Multiplication

```
{
  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;
}
```

%ecx	result
%edx	j
%esi	n
%ebx	jTnPk
Mem[-4(%ebp)]	iTn

Inner Loop

```
.L44:                         # loop
  movl -4(%ebp),%eax          # iTn
  movl 8(%ebp),%edi           # a
  addl %edx,%eax              # iTn+j
  movl (%edi,%eax,4),%eax     # a[iTn+j]
  movl 12(%ebp),%edi          # b
  incl %edx                   # j++
  imull (%edi,%ebx,4),%eax    # b[jTnPk]*a[iTn+j]
  addl %eax,%ecx              # result += ..
  addl %esi,%ebx              # jTnPk += n
  cmpl %esi,%edx              # j : n
  jl .L44                     # if < goto loop
```


Summary

Arrays in C

- Contiguous allocation of memory
- Pointer to first element
- No bounds checking

Compiler Optimizations

- Compiler often turns array code into pointer code `zd2int`
- Uses addressing modes to scale array indices
- Lots of tricks to improve array indexing in loops
  - code motion
  - reduction in strength