Low-Level C Programming

Memory map

Pointers

Arrays

Structures

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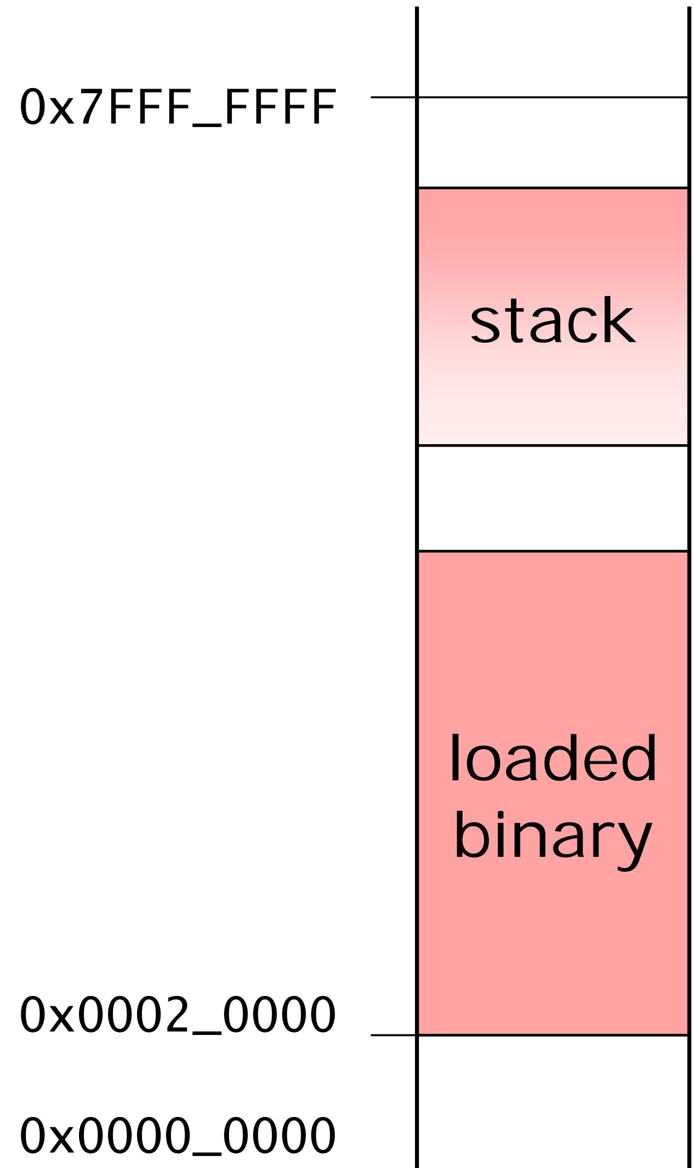
Memory Map

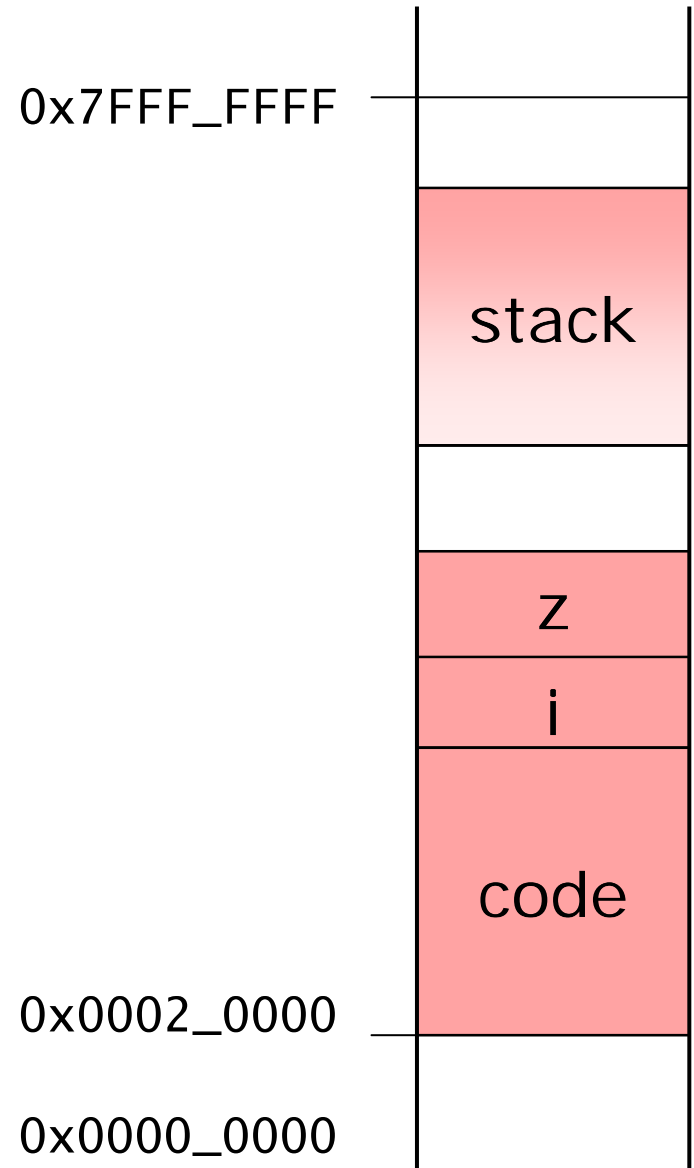
- Binaries load at 0x20000 by default
- Stack start set by binary when started
- Stack grows downwards
- You will need one stack for each task



Information Technology

Binaries

- Code
  - All functions of your program
- Static data
  - Global variables
  - Static variables
  - Initialized
  - Uninitialized/zeroed
- All loaded into memory at startup



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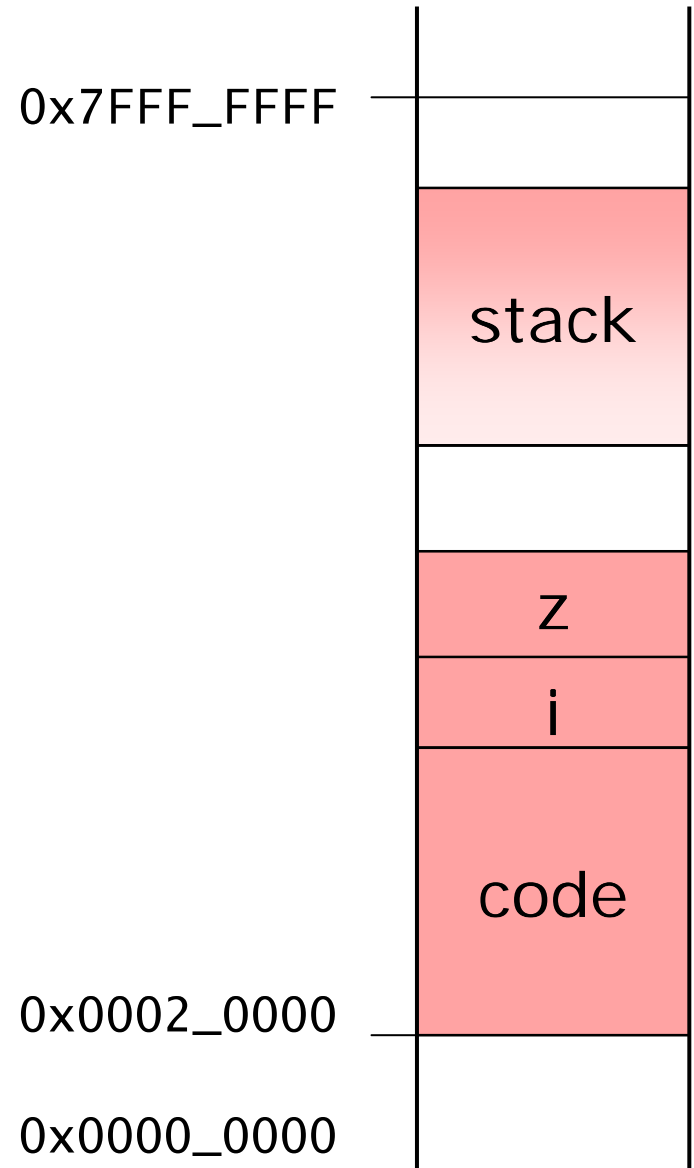
Variables

- All variables have an address
  - Stack
    - "auto" variables
    - allocated when function called
    - varies with each function call
  - Global variables
    - z/i areas
    - fixed for entire execution of program



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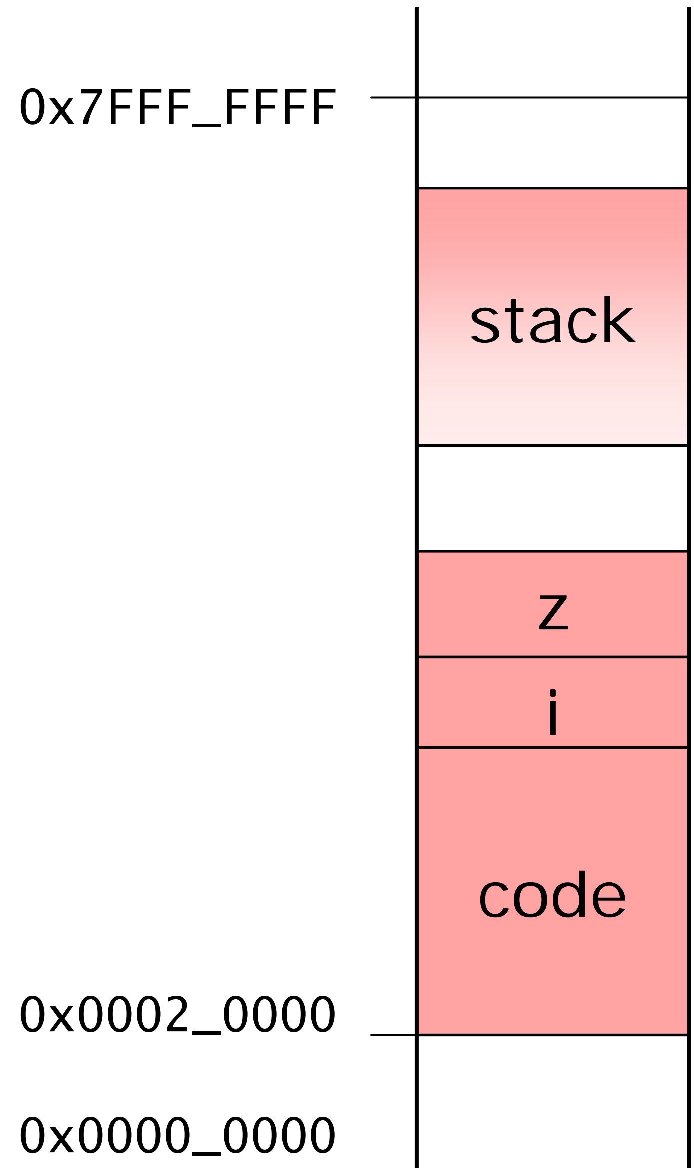
Functions

- All functions have an address
  - code area
  - fixed for entire execution of program



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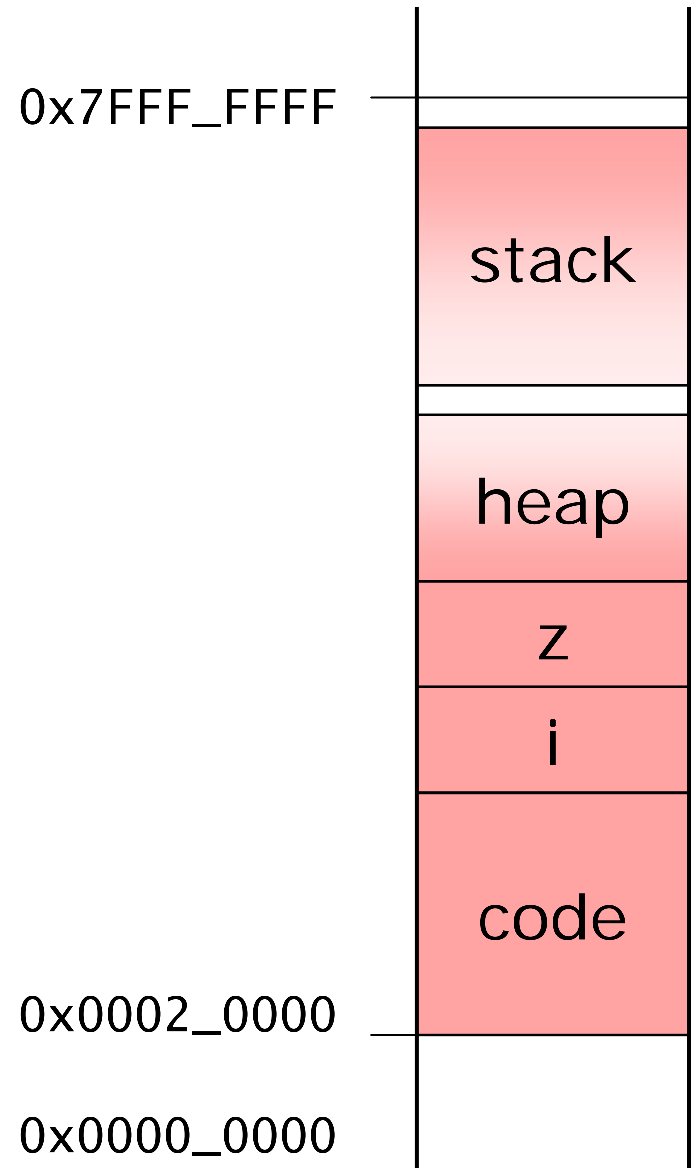
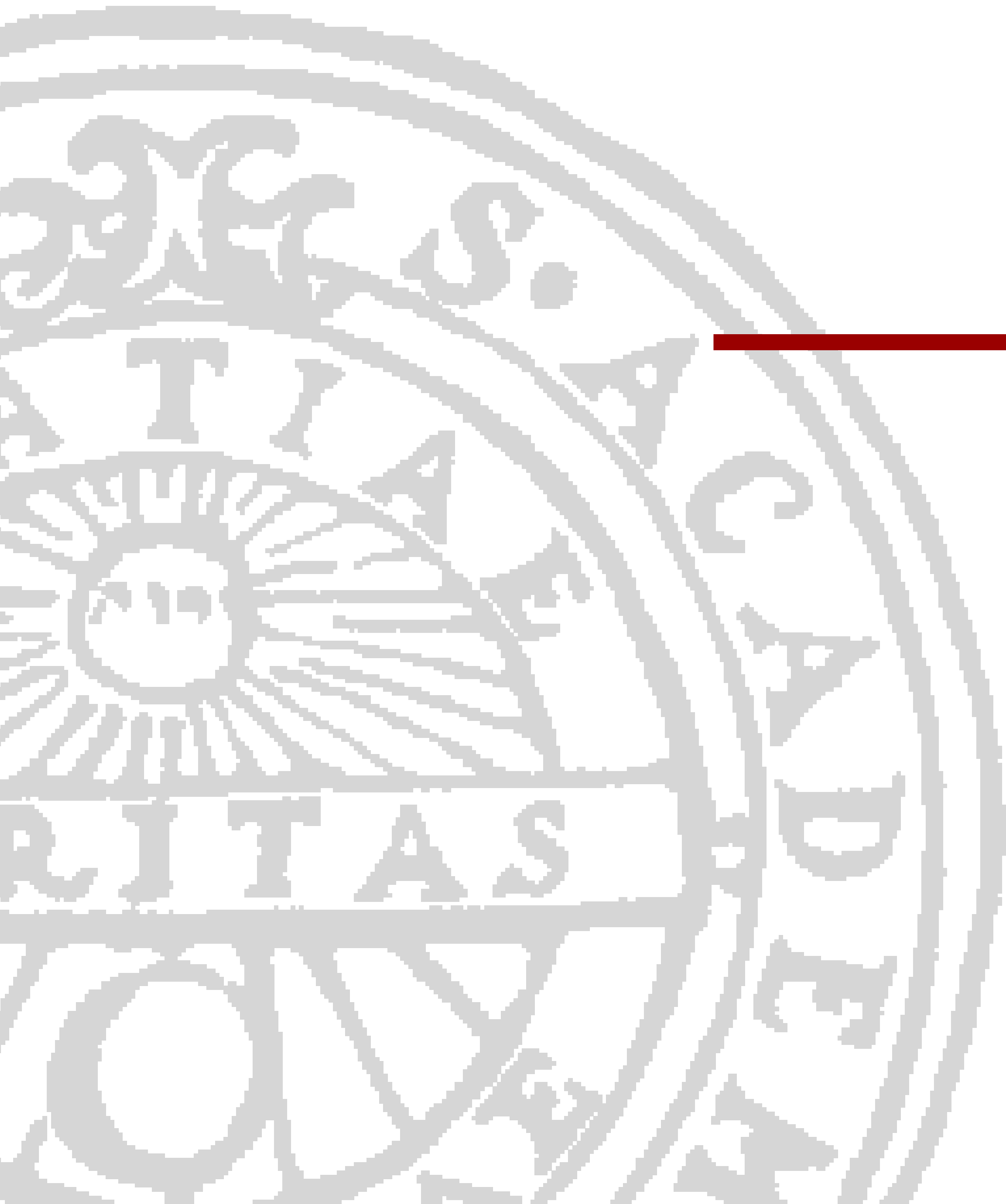
Heap

- For dynamic memory allocation
  - Allocated at need
  - Explicit functions
    - “malloc”
- Not mandatory in your project!





Pointers

Basic pointer

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Pointer

- Variable that contains address
  - Of another variable
    - Global
    - Stack
  - Of dynamically allocated memory
- Must be given something to point at
  - Declaring a pointer does not do this
  - Always initialize a pointer!

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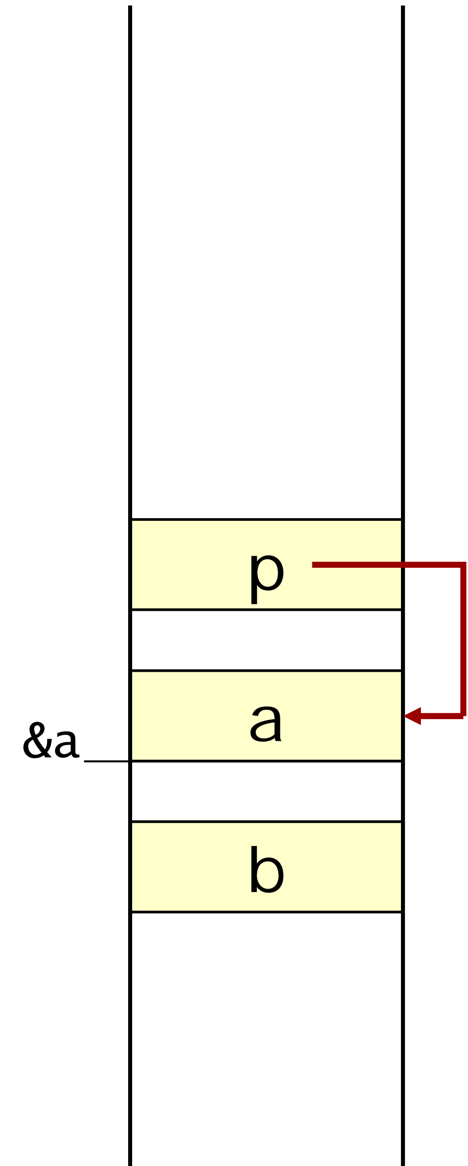
Basic pointer

- `int  a   // variable`
- `int  b`
- `int *p   // pointer to int`

- `a =  7   // a=7`
- `p = &a   // p points to a`
- `b = *p   // b=a=7`
- `*p = 5   // a=5, b=7`

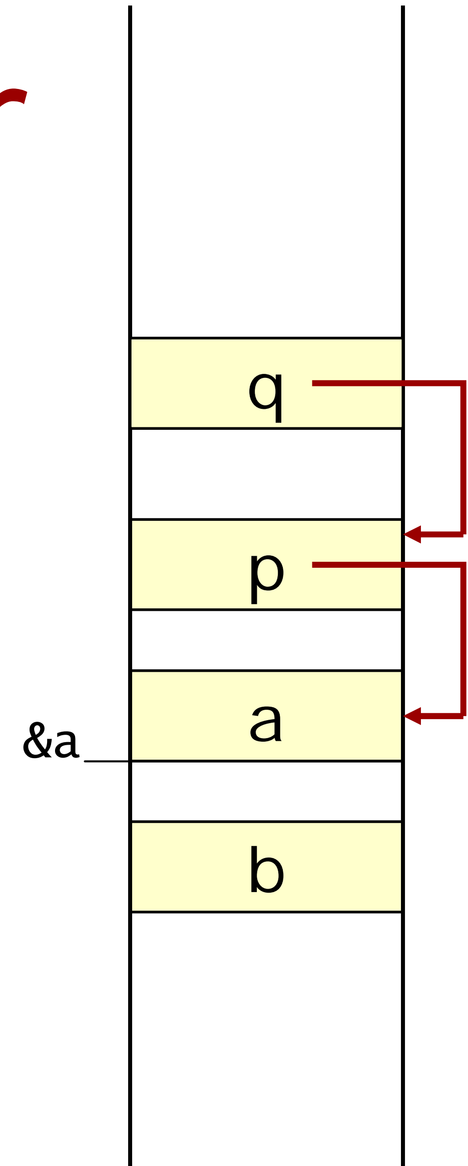


Information Technology

Pointer to pointer

- `int  a   // variable`
- `int  b`
- `int *p   // pointer to int`
- `int **q  // ptr to ptr to int`

- `a =  7   // a=7`
- `p = &a   // p points to a`
- `q = &p   // q points to p`
- `b = *p   // a=7, b=7`
- `*p = 5   // a=5, b=7`
- `**q = 3  // a=3, b=7`



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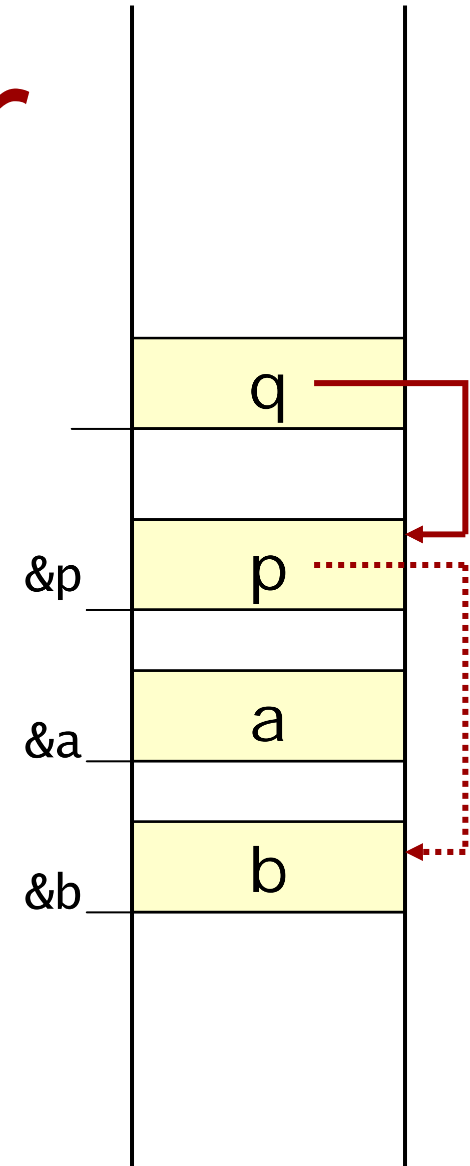
Pointer to pointer

- `int  a   // variable`
- `int  b`
- `int *p   // pointer to int`
- `int **q  // ptr to ptr to int`

- `p = &a   // p points to a`
- `q = &p   // q points to p`
- `*q = &b  // repoint p to b`
- `*p = 1   // b=1`



Pointers & types

- Pointer points to a particular type
- Can only legally address objects of that type
  - Assign "`char*`" to "`int*`" is an error
- Each type has a size
  - char = 1 byte
  - short int = 2 bytes
  - int = 4 bytes (on MIPS32)
  - etc.

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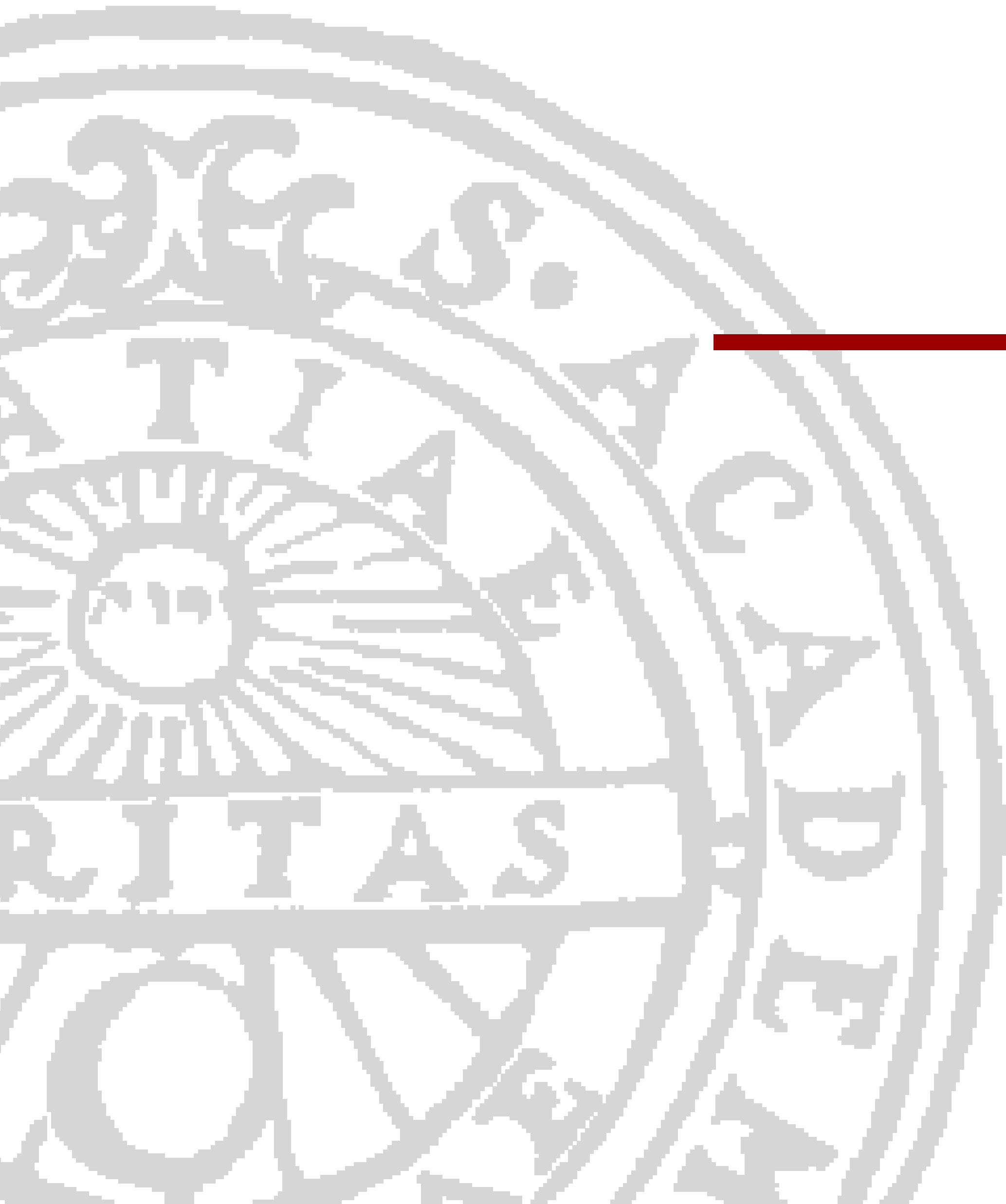
Pointers & types

- Special pointer type: void
  - Compatible with all types
  - Use with care!
  - Cannot be dereferenced!
    - What is the type of the object? None!



Arrays

Identical
things
in a row

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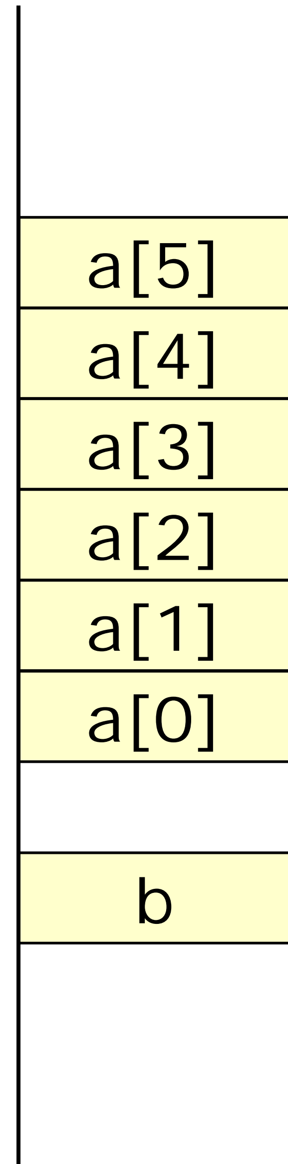
Basic arrays

- `int  a[6] // array`
- `int  b`

- `a[0] = 1    // assign element`
- `b = a[2]    // read element`
- `a[b] = a[5] // variable index`
- `a[17] = 2   // danger!`

- Notes
  - zero-based indexing
  - no bounds checking
  - higher index=higher address



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Array initializers

- Initialize & size array
- `int  a[]={1,1,2,3,5,8,13}`
  - 7 elements
  - equivalent size: a[7]

13
8
5
3
2
1
1

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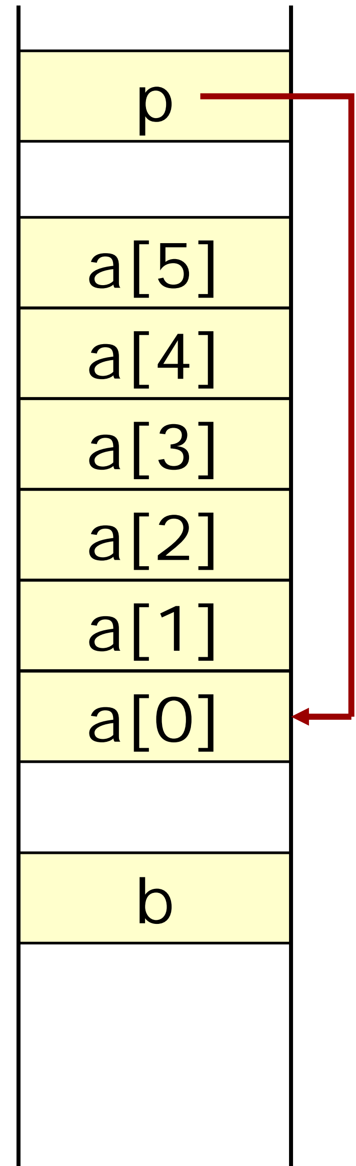
Arrays = pointers

- In C, array == pointer
  - Array variable = address of first element of array

```
int   a[6] // array
int   b
int  *p
```

```
p = a
p = &a[0]  // equivalent
// p = &b would point to b
```



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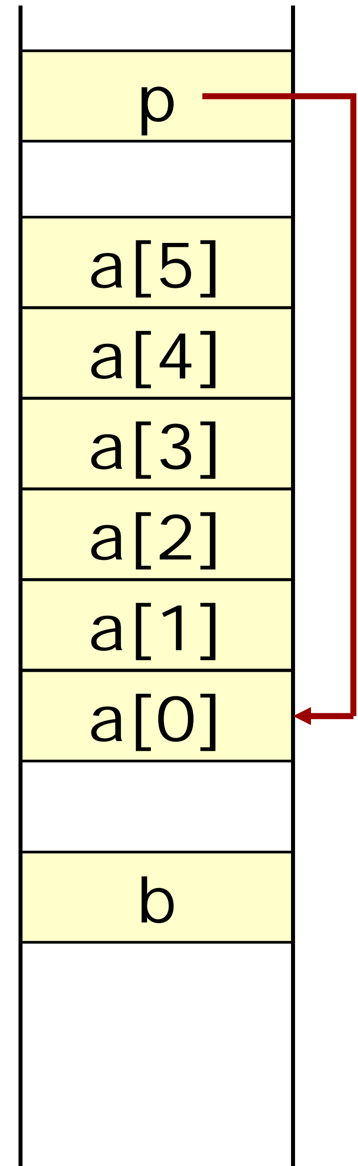
Arrays = pointers

- Index from pointer

```
int   a[6] // array
int   b
int  *p

p = a
b = (*p)[5] // () needed!
b = *p      // b=a[0]
```



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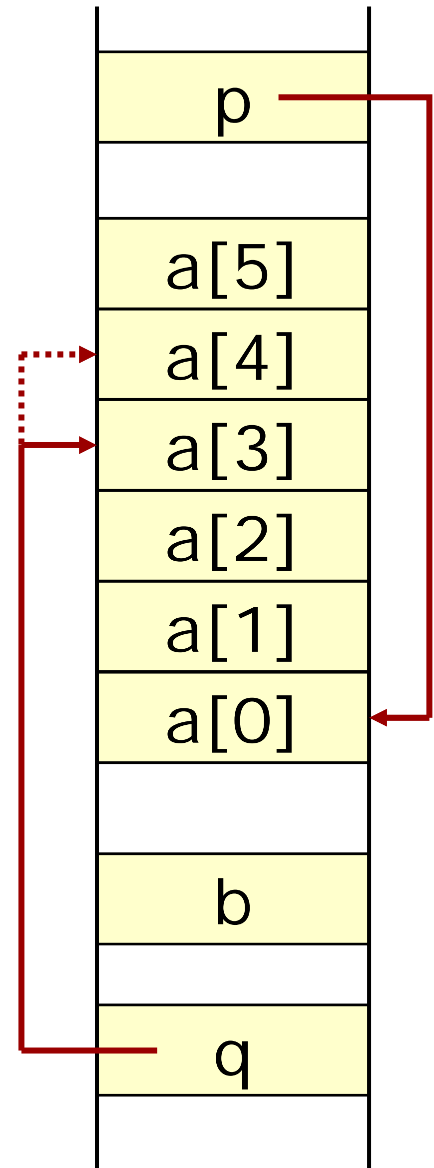
Arrays = pointers

- Indexing = arithmetic
  - a[x] == *(a+x)

```
int   a[6] // array
int   b
int  *p, *q
q = p+3    // q=&a[3]
q++        // step to next
b = *q     // b=a[4]
b = *(p+1) // b=a[1]
b = q-p    // pointer difference
```



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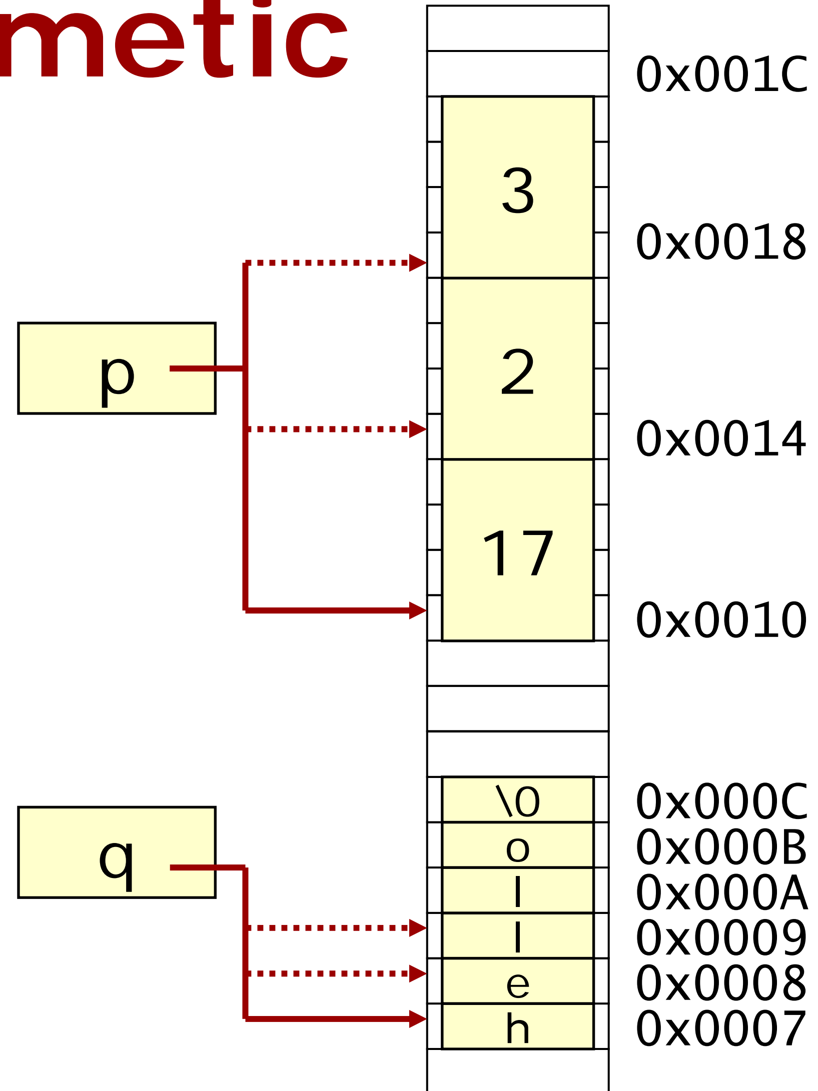
Pointer Arithmetic

- Unit of operation: size of type
  - `int  *p`
  - `char *q`
  - `p++`
  - `p++`
  - `q++`
  - `q++`



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sizeof

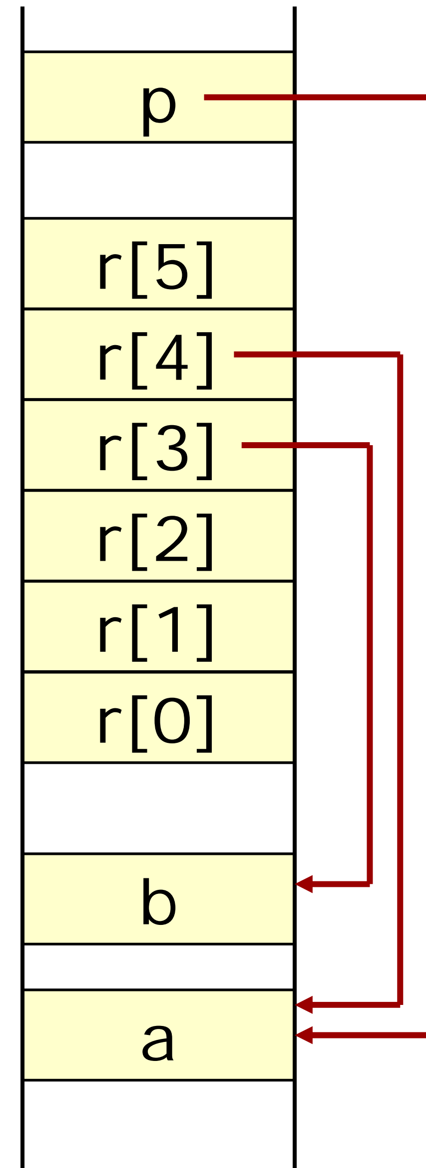
- sizeof operator defined in C
- Gives the size in #of bytes of a type
- Used to step pointers

Information Technology

Arrays of pointers

- `int  *r[6] // array of ptr`
- `int  *p`
- `int   b`
- `int   a`

- `p = &a`
- `r[3] = &b`
- `*r[3] = 7  // b=7`
- `r[4] = p`



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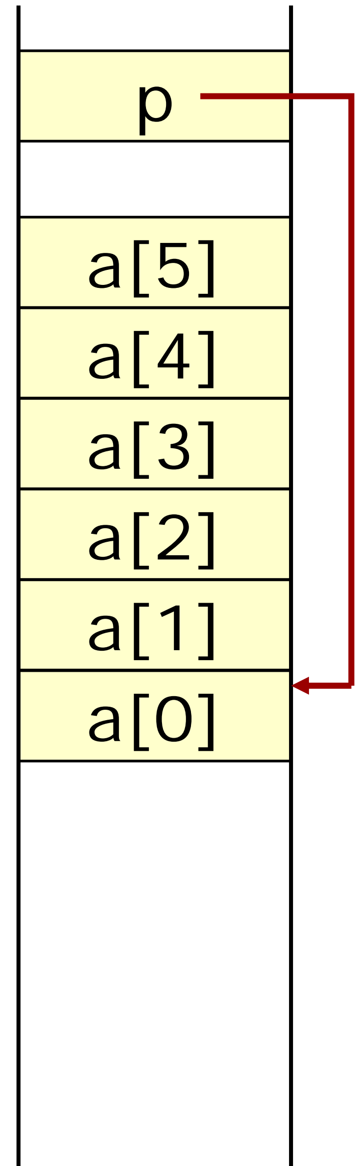
Pointer to array

- `int  (*p)[6] // ptr to array`
- `int  a[6]`

- `p = &a  // correct`

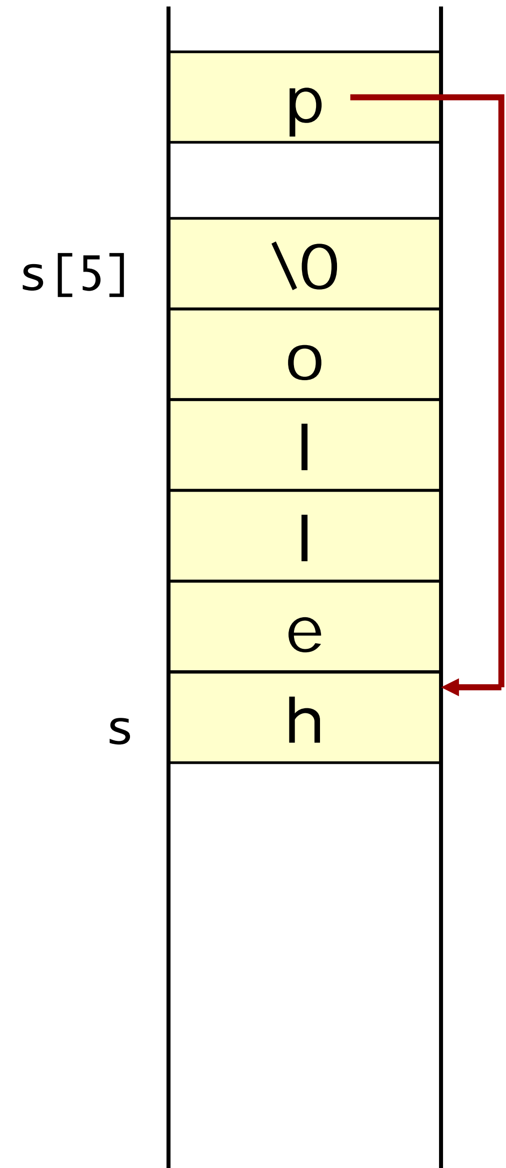


Information Technology

Strings

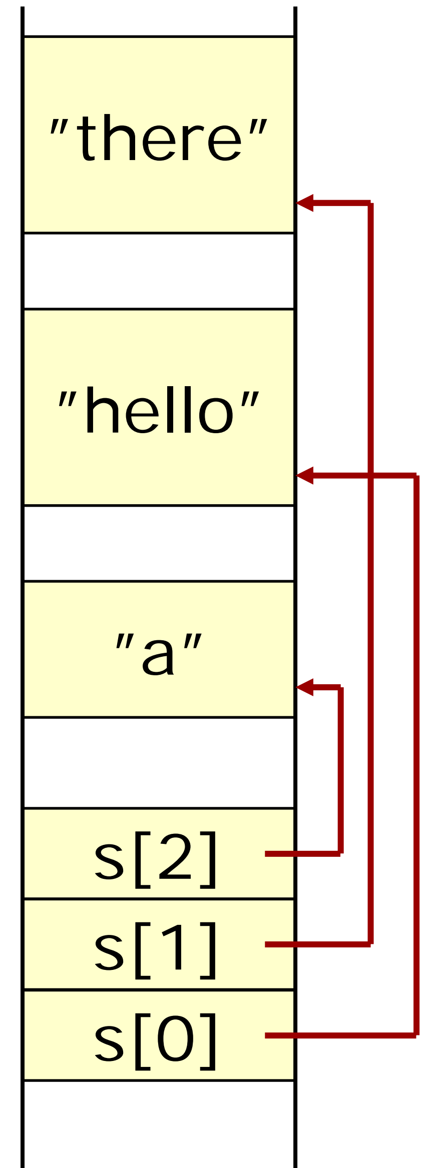
- String = array of char
  - Special initializer syntax
  - No other support in C
  - Null-terminated

```
char s[] = “hello”
char *p
p = s
*p = ’w’        // s[0]=w
*p = s[4]       // s[0]=o
```



Array of Strings

- Array of char*
  - Each string separate
  - Stored in constant memory
  - Not contiguous
- `char *s[]={“hello”,“there”,”a”}`



Information Technology

Arrays as parameters

- Passed as pointer, not value
- No check for size of array

```
void foo(char a[])
{
    int i;
    for(i=0;i<MAX_SIZE;i++)
    {
        ...a[i]...
    }
}
```

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Arrays as parameters

- Pointer is alternative, equivalent

```
void foo(char *a, int b)
{
    int i;
    for(i=0;i<b;i++)
    {
        ...a[i]...
        ...*a++...
    }
}
```

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Iterating over Strings

- Compute the length of a string:
  - Watch for the zero termination!

```
int length (const char * s)
{
  char *p=s;
  while( *p != '\0' )
   p++;
  return p-s;
}
```

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Local Arrays

- Allocated on the stack
- Not cleared before use
  - Always initialize
  - Contains garbage data when created
- Deallocated when function returns
  - Do not return a local pointer!

Structures

Organizing data
into records

Structures in C

- Collection of related data
  - Use typedef for clarity
- Syntax:

```
typedef struct TAG {  // TAG is optional but good form
   TYPE  element;
   TYPE2 element2;
   ...
} TAG_T;

TAG_T x; // declare variable
```

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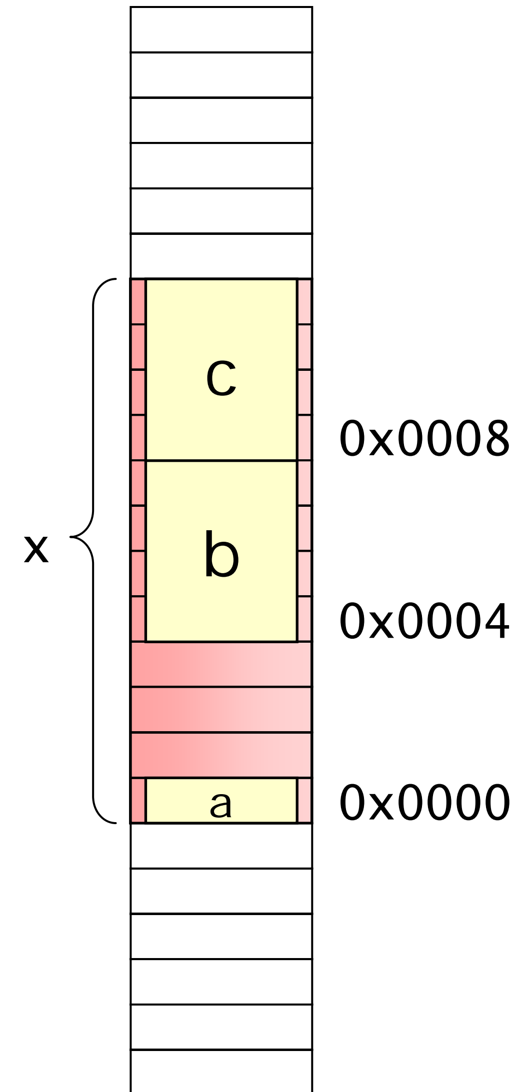
Information Technology

In Memory

- Elements stored in order
- Potentially padded
  - To align evenly in memory
- Towards higher addresses

```
struct bar {
  char  a;   // 1 byte
             // invisible 3-byte padding
  int   b;   // 4 bytes
  int  *c;   // 4 bytes
} x;
```

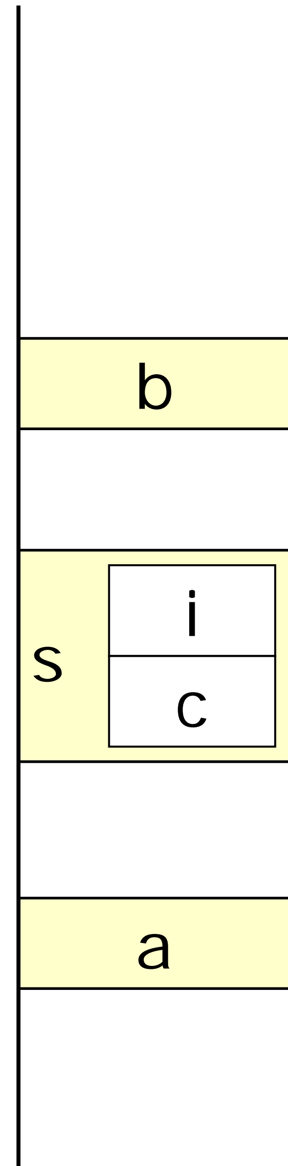


Information Technology

Structs

- ```
  typedef struct {
    int  i;
    char c;
  } S_t ;
  ```
- `S_t  s`
- `int  a = 112`
- `char b = ‘y’`

- `s.i = a`
- `s.c = ‘x’`
- `b = s.c`

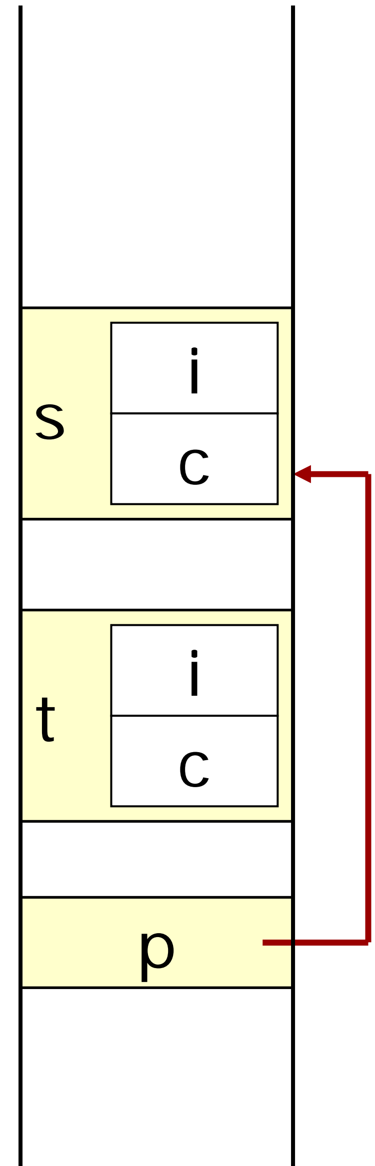

  ```

Information Technology

Struct Pointers

```
S_t  s
S_t  t
S_t *p

p = &s          // p points at s
(*p).i = t.i    // assign element
p->i = t.i      // special syntax!
t = *p          // t=s
```

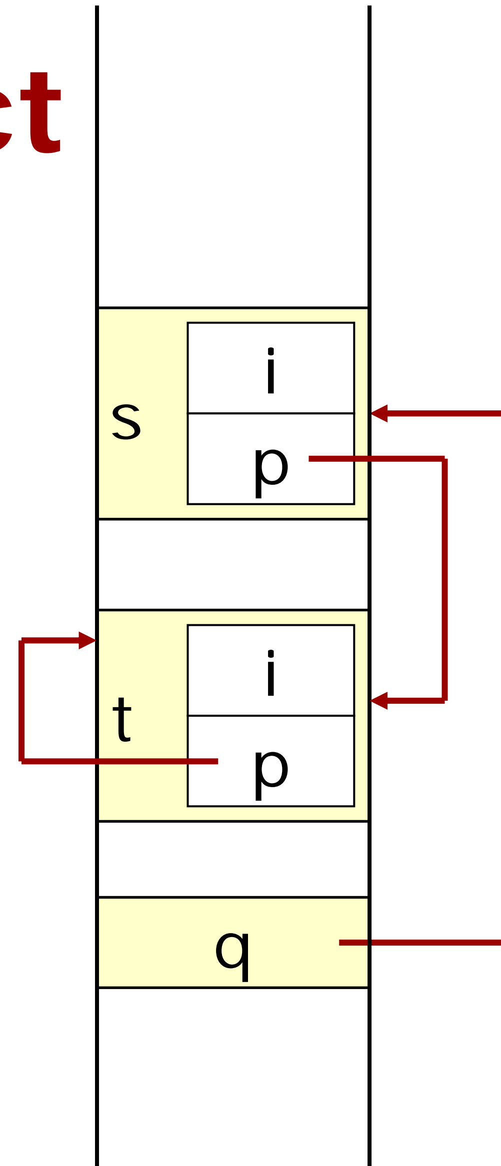


Information Technology

Struct Ptr in Struct

- ```
  typedef struct T {
    int        i;
    struct T *p;  // ptr to own type
  } T_t
  ```
- `T_t  s`
- `T_t  t`
- `T_t *q      // “struct T* q”`

- `q = &s`
- `q->p = &t  // changing s.p`
- `t.p = s.p  // t points to itself`


  ```

Structure Parameters

- Call-by-value
  - Gets copied to the stack of the callee

```
void foo(struct bar x, int b)
{
  ...x.a...
}
```

Information Technology

Structure Initialization

- Initialize all elements of a struct

```
struct bar z = {'a', 45, &b};
```

- Combine with array initializers

```
struct bar z[3] = { {'a', 45, &b},
                    {'b', 47, &c},
                    {'d', 10, &d} }
```

Linked Lists

Structs

+

Pointers

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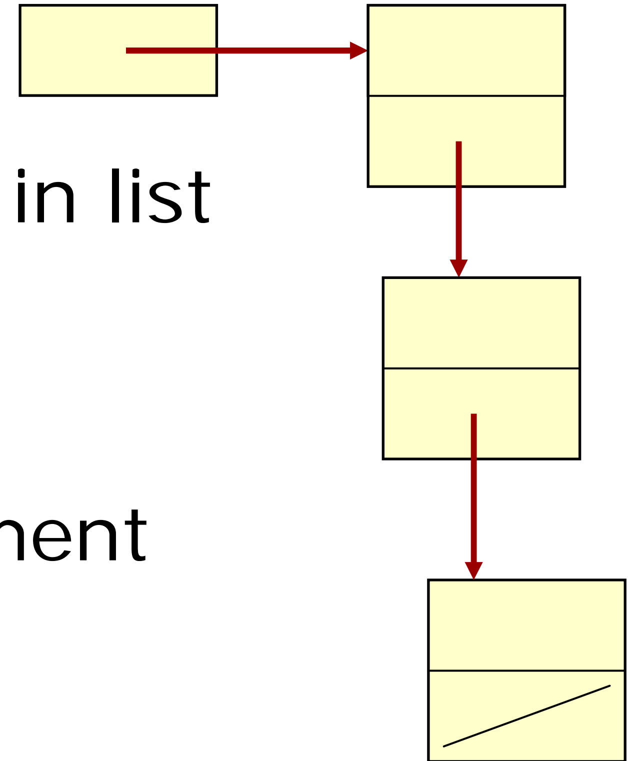
Linked list



- Head pointer
  - Points at first element in list
  - Outside the list per se
- Next pointer
  - Points to the next element
  - Stored inside the list
- End marked by NULL
- Elements are structs in C

Information Technology

Defining a list

- Element type:
  - ```
    typedef struct T {
      int        value;    // short: v
      struct T *next;      // short: n
    } T_t
    ```
- Head pointer:
  - `T_t *head`
  - `head = NULL`

    ```

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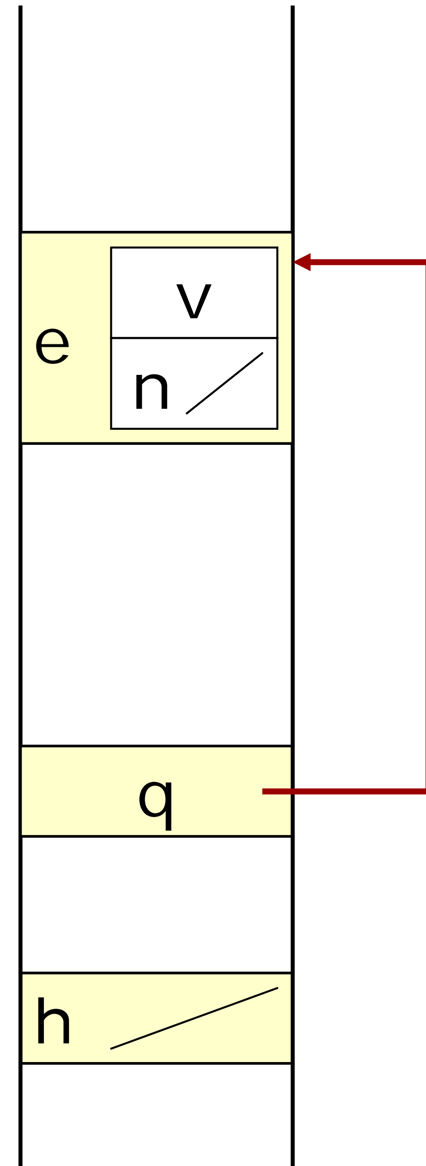
# First element

- Create a new element
  - Declare as variable
  - Allocate dynamically
  - We get a pointer to it

```
T_t e
T_t *q
e.n = NULL // initialize!
q = &e   // ptr to newcomer
```



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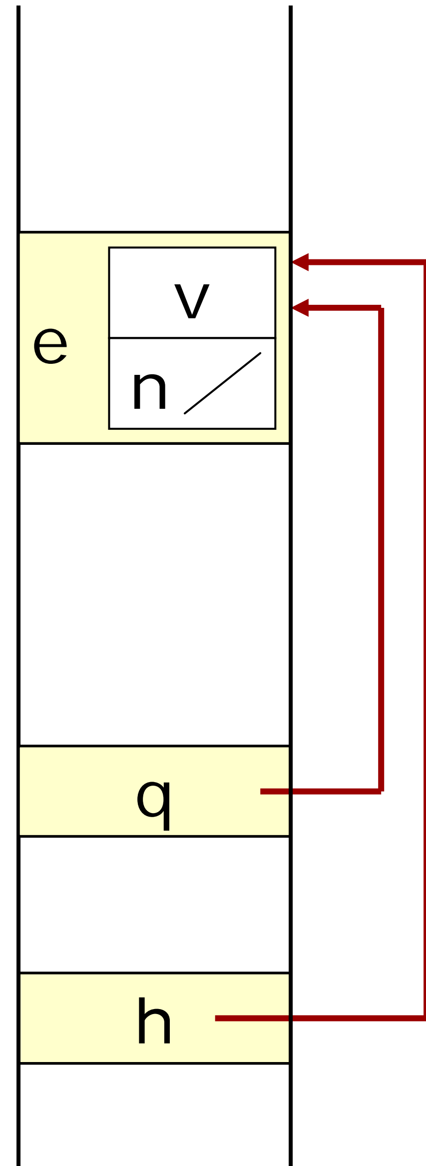
Insert into list

- Update head
  - `head = q   //`
  - `q = &e     // ptr to newcomer`
- First element
  - Special case



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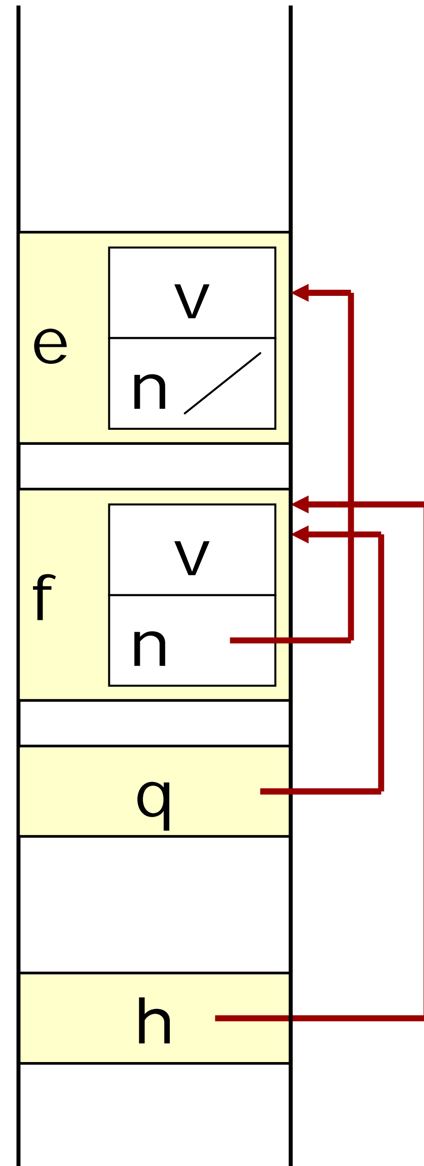
One more

- Link in at start of list
  - Update head
    - But first new element points at the old head of the list!

```
T_t  f       // new element
f.n = NULL   // initialize next
   q = &f
q->n = h
   h = q
```

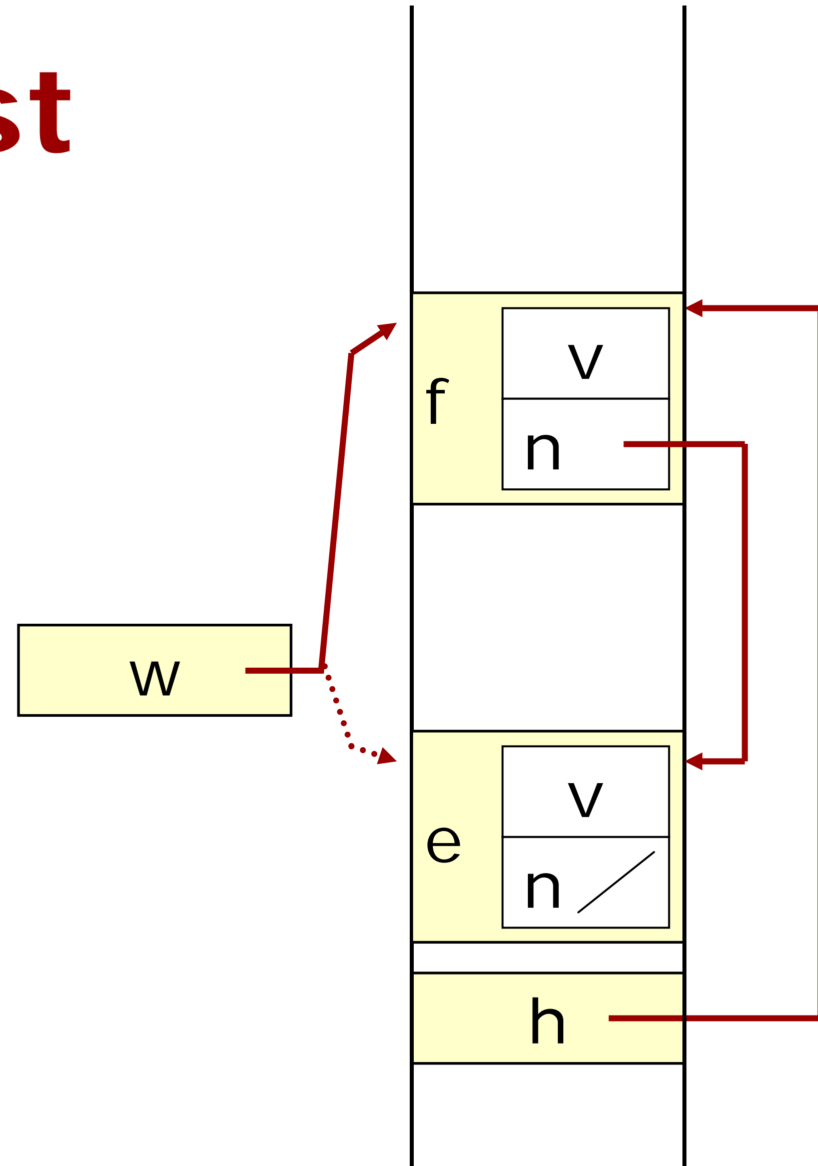


Information Technology

Traverse a list

- Visit all elements
  - Start at head
  - Use a “walker”

```
T_t *w  // walker
w = h   // start
while(w!=NULL)
{
  visit(w)
  w = w->next
}
```



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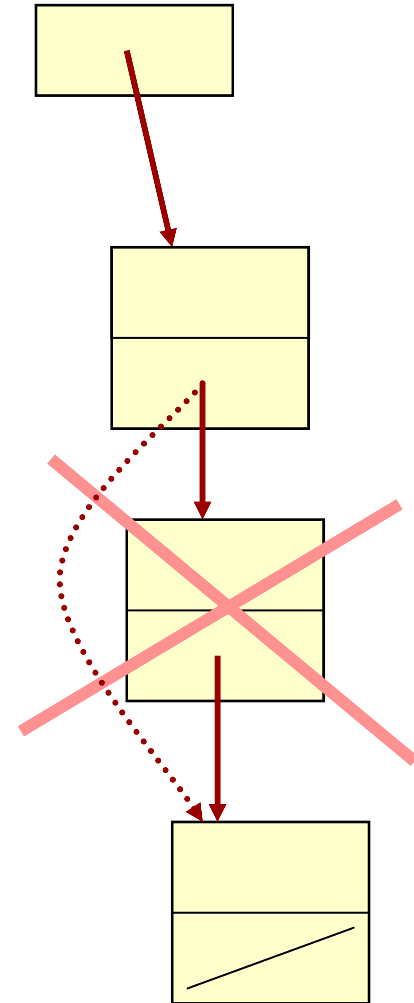
Remove element

- Link “over” the element
  - Change the predecessor
    - Special case for head!
  - Unlink it from the list
    - Make removed element have NULL next pointer



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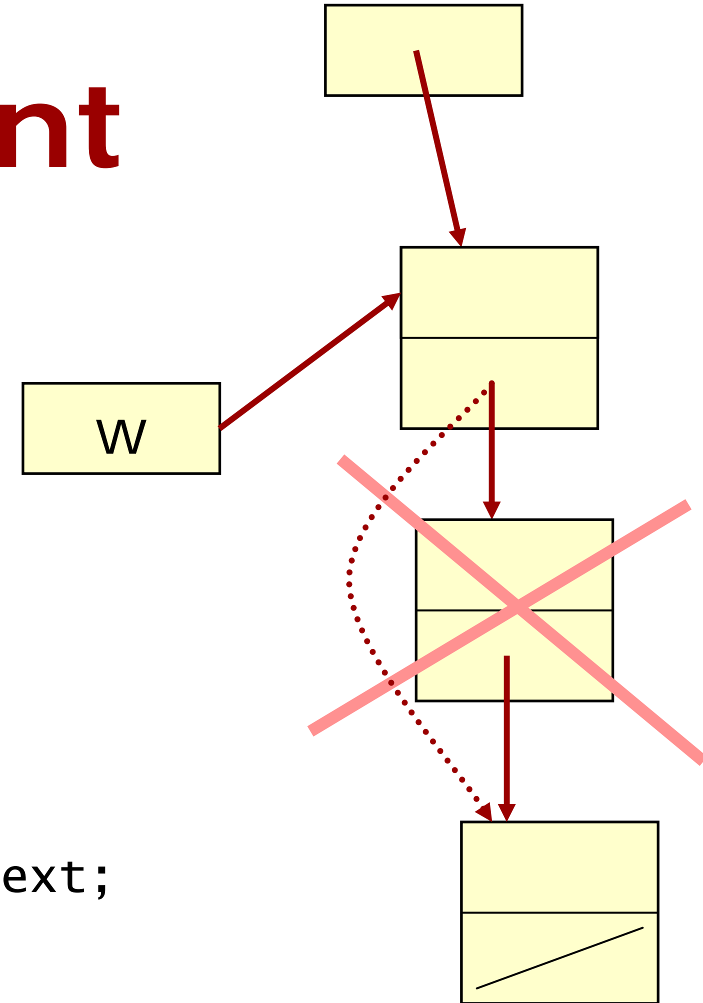
Remove element

- Example function
  - ```
    void remove( T_t *e )
    {
      if (h==e)
        h = h->next;
      else {
        T_t *w = h;
        while(w!=NULL) {
          if(w->next == e)
            w->next = w->next->next;
          w = w->next;
        }
      }
      e->next = NULL;
    }
    ```


    ```

Arrays of Structures

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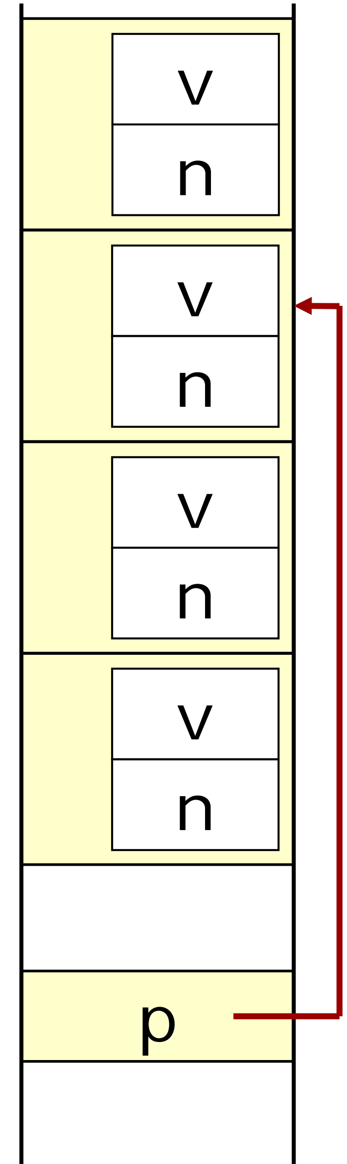
Array of Structures

- `T_t  a[4]`
- `T_t  t = {10,NULL}`
- `T_t *p`

- `a[0] = t`
- `p = a+2  // p = &a[2]`
- `*p = t`
- `a[1] = a[3]`



Static Memory

- Global array of struct:
  - Statically allocated
  - Gives you a memory area to work on
  - Good alternative to malloc() in OS

Exercises

To work on to familiarize yourself with pointeres

Information Technology

Exercises

- Work on Sun/Linux/Windows
  - Get it right on host first!
  - Use malloc() to create elements
    - `T_t *p = malloc( sizeof(T_t) )`
  - Use printf() to see contents of lists

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Sorted linked list

- Create a linked list that is always sorted, with the following functions:
  - `newelement(value)`: creates a new element using malloc()
  - `insert(list,newelement)`: inserts the new element in the right place in the list
  - `delete(list,element)`: removes the element from the list
  - `print(list)`: print the list

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Double-linked lists

- Each element has two pointers:
  - next and previous
- Basic functions to create:
  - No requirements for sorting here!
  - `newelement(value)`
  - `insert(list,newelement)`
  - `insert_after(list,element,newelement)`
  - `delete(list,element)`
  - `print(list,direction)`

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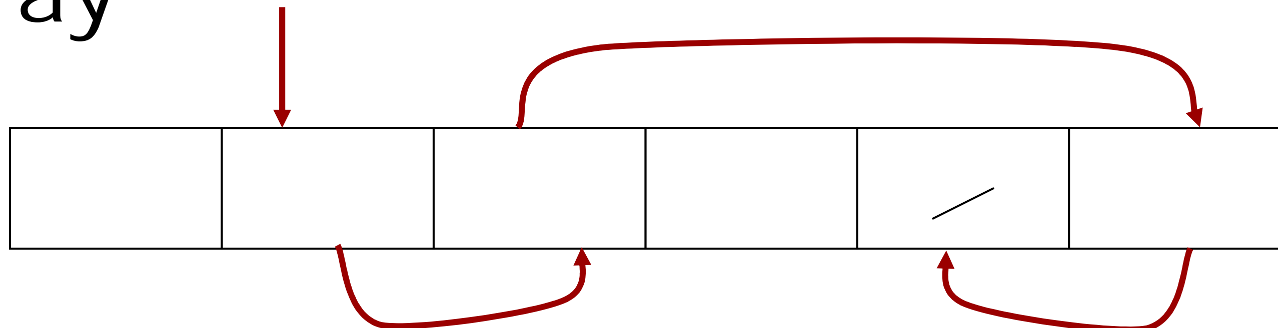
Linked list in array

- Declare a large array
  - T_t a[1000]
- Instead of malloc(), allocate new elements from unused array items
- "Thread" the linked list through the array



Information Technology

Linked list in array

- Two lists:
  - Used elements
  - Unused/free elements
- Allocate = move from free to used
  - Find a free item
  - Relink to the other list