Pointers and Linked Lists

Pointer Overview

Basic computer memory abstraction.

- Indexed sequence of binary numbers.
- Address = index.

Pointer = variable that stores memory address.

Uses.

- Allow function to change inputs.
- Better understanding of arrays.
- Create "linked lists."

Pointers

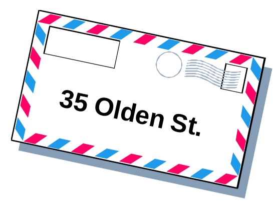
Variable that stores the value of a single MEMORY LOCATION.

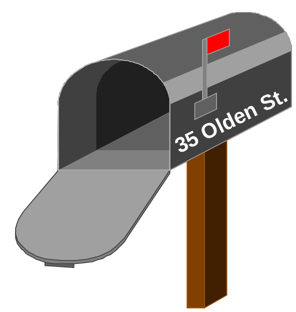
- In TOY, memory locations are 00 – FF.
  - indexed addressing: store a memory location in a register
- Very powerful and useful programming mechanism.
- Confusing and easy to abuse!

Address	D000	D004	D008	..	D0C8	D0CC	D0D0	..	D200	D204	D208
Value	9	1	D200	..	0	7	0000	..	5	3	D0C8

Memory location D008 stores a "pointer" to another memory location of interest.

Pointer Intuition





Mailbox corresponds to unit of computer memory.
Postal address corresponds to memory address (pointer).

Pointers in C

C pointers.

- If x is an integer
  - &x is the memory location of x.
- If px is a pointer to an integer
  - *px is the integer.

Unix

```
% gcc pointer.c
% a.out
  x = 7
 px = ffbefb24
*px = 7
```

allocate storage for pointer to int

pointer.c

```
#include <stdio.h>

int main(void) {
  int x;
  int *px;

  x = 7;
  px = &x;
  printf("  x = %d\n");
  printf(" px = %p\n", px);
  printf("*px = %d\n", *px);
  return 0;
}
```

Pointers as Arguments to Functions

Goal: write a function to swap the values of two different integer variables.

A first attempt:

only swaps copies of x and y

badswap.c

```
#include <stdio.h>

void swap(int a, int b) {
  int t;
  t = a; a = b; b = t;
}

int main(void) {
  int x = 7, y = 10;
  swap(x, y);
  printf("%d %d\n", x, y);
  return 0;
}
```

Pointers as Arguments to Functions

Goal: write a function to swap the values of two different integer variables.

Now, one that works.

changes value stored in memory address for x and y

swap.c

```
#include <stdio.h>

void swap(int *pa, int *pb) {
  int t;
  t = *pa; *pa = *pb; *pb = t;
}

int main(void) {
  int x = 7, y = 10;
  swap(&x, &y);
  printf("%d %d\n", x, y);
  return 0;
}
```

Pointers and Arrays

avg.c

```
#include <stdio.h>
#define N 64

int main(void) {
  int a[N] = {84, 67, 24, ..., 89, 90};
  int i, sum;

  for (i = 0; i < N; i++)
    sum += a[i];

  printf("%d\n", sum / N);
  return 0;
}
```

integer (on arizona) takes 4 bytes $\Rightarrow$ 4 byte offset

"Pointer arithmetic"

```
&a[0] = a+0   = D000
&a[1] = a+1   = D004
&a[2] = a+2   = D008

 a[0] = *a     = 84
 a[1] = *(a+1) = 67
 a[2] = *(a+2) = 24
```

Memory address	D000	D004	D008	..	D0F8	D0FC	..
Value	84	67	24	..	89	90	..

Passing Arrays to Functions

In C, when array is passed to a function, a pointer to first element of array is passed.

avg.c

```
#include <stdio.h>
#define N 64

int average(int b[], int n) {
  int i, sum;
  for (i = 0; i < n; i++)
    sum += b[i];
  return sum / n;
}

int main(void) {
  int a[N] = {84, 67, 24, ..., 89, 90};
  printf("%d\n", average(a, N));
  return 0;
}
```

← receive the value D000 from main (at `int average(int b[], int n) {`)

← passes &a[0] = D000 to function (at `printf("%d\n", average(a, N));`)

Why Pass Array as Pointer?

Advantages.

- Efficiency for large arrays – don't want to copy entire array.
- Easy to pass "array slice" of "sub-array" to functions.

avg.c

```
int average(int b[], int n) {
  int i, sum;
  for (i = 0; i < n; i++)
    sum += b[i];
  return sum / n;
}

int main(void) {
. . .
  res = average(a+5, 10);
. . .
}
```

← compute average of a[5] through a[14] (at `res = average(a+5, 10);`)

Passing Arrays to Functions

Some C programmers use `int *b` instead of `int b[]` in function prototype to emphasize that arrays decay to pointers when passed to functions.

average function

```
int average(int b[], int n) {
  int i, sum;
  for (i = 0; i < n; i++)
    sum += b[i];
  return sum / n;
}
```

a completely equivalent function

```
int average(int *b, int n) {
  int i, sum;
  for (i = 0; i < n; i++)
    sum += b[i];
  return sum / n;
}
```

Linked List Overview

Goal: deal with large amounts of data.

- Organize data so that it is easy to manipulate.
- Time and space efficient.

Basic computer memory abstraction.

- Indexed sequence of binary numbers.
- Address = index.

Need higher level abstractions to bridge gap.

- Array
- Struct
- LINKED LIST

Linked List

Fundamental data structure.

- HOMOGENEOUS collection of values (all same type).
- Store values ANYWHERE in memory.
- Associate LINK with each value.
- Use link for immediate access to the NEXT value.

special "NULL" memory address denotes end of list

Possible memory representation of $x^9 + 3x^5 + 7$.

- Assume linked list starts in location D000.

Address	D000	D004	D008	..	D0C8	D0CC	D0D0	..	D200	D204	D208
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exponent coefficient memory address of next element

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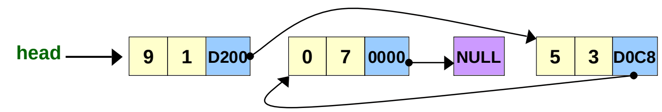

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- Advantage: space proportional to amount of info.
- Disadvantage: can only get to next item quickly.

Linked List vs. Array

Polynomial example illustrates basic tradeoffs.

- Sparse polynomial = few terms, large exponent.
  Ex. $x^{1000000} + 5x^{50000} + 7$
- Dense polynomial = mostly nonzero coefficients.
  Ex. $x^7 + x^6 + 3x^4 + 2x^3 + 1$

Huge Sparse Polynomial		
	array	linked
space	huge	tiny
time	instant	tiny

Huge Dense Polynomial		
	array	linked
space	huge	3 * huge
time	instant	huge

Time to determine coefficient of x^k.

Space vs. Time Tradeoffs

Axiom 1: there is never enough space.
Axiom 2: there is never enough time.

It is easy to write programs that waste both.

- You will not notice until it matters.

Lesson: know space and time costs.

Overview of Linked Lists in C

Not directly built in to C language. Need to know:

How to associate pieces of information.

- User-define type using `struct`.

How to specify links.

- Linked list element contains information (coefficient and exponent) and MEMORY LOCATION of next linked list element.
- Need to use pointers.

How to reserve memory to be used.

- Allocate memory DYNAMICALLY (as you need it).
- `malloc`

How to use links to access information.

- `->` and `.` operators

Linked List for Polynomial

C code to represent of $x^9 + 3x^5 + 7$.

- Statically, using nodes.

poly1.c

```
typedef struct node *link;
struct node {
   int coef;
   int exp;
   link next;
};

int main(void) {
   struct node p, q, r;

   p.coef = 1; p.exp = 9;
   q.coef = 3; q.exp = 5;
   r.coef = 7; r.exp = 0;

   p.next = &q;
   q.next = &r;
   r.next = NULL;

   return 0;
}
```

- define node to store two integers
- memory location of next node
- initialize data
- link up nodes of list

Linked List for Polynomial

C code to represent of $x^9 + 3x^5 + 7$.

- Statically, using nodes.
- Dynamically using links.

poly2.c

```
#include <stdlib.h>

typedef struct node *link;
struct node { . . .};

int main(void) {
   link x, y, z;

   x = malloc(sizeof(struct node));
   x->coef = 1; x->exp = 9;
   y = malloc(sizeof(*link));
   y->coef = 3; y->exp = 5;
   z = malloc(sizeof(*z));
   z->coef = 7; z->exp = 0;

   x->next = y;
   y->next = z;
   z->next = NULL;

   return 0;
}
```

- initialize data
- allocate enough memory to store node
- link up nodes of list

Study this code: tip of iceberg!

Better Programming Style

Write separate function to handle memory allocation and initialization.

poly3.c

```
#include <stdlib.h>
#include <assert.h>

link NEWnode(int c, int e, link n) {
  link x = malloc(sizeof(struct node));
  assert(x != NULL);
  x->coef = c; x->exp = e; x->next = n;
  return x;
}

int main(void) {
  link x, y, z;
  x = NEWnode(1, 9, NULL);
  y = NEWnode(3, 5, NULL);
  z = NEWnode(7, 0, NULL);
  x->next = y; y->next = z; z->next = NULL;
  return 0;
}
```

check if malloc fails (→ `assert(x != NULL);`)

Review of Stack Interface

In Lecture P5, we created ADT for stack.

- We implemented stack using arrays.
- Now, we give alternate implementation using linked lists.

STACK.h

```
void STACKinit(void);
int  STACKempty(void);
void STACKpush(int);
int  STACKpop(void);
```

client.c

```
#include "STACK.h"

int main(void) {
  int a, b;
  . . .
  STACKinit();
  STACKpush(a);
  . . .
  b = STACKpop();
  return 0;
}
```

client uses data type, without regard to how it is represented or implemented.

Stack Implementation With Linked Lists

Push and pop at the front of list.

stacklist.c

```
#include <stdlib.h>
#include <assert.h>
#include "STACK.h"

typedef struct STACKnode* link;
struct STACKnode {
   int item;
   link next;
};

static link head;

void STACKinit(void) {
   head = NULL;
}

int STACKempty(void) {
   return NULL == head;
}
```

- standard linked list data structure (→ `struct STACKnode`)
- use static to make it a true ADT (→ `static link head;`)
- head points to first node in linked list (→ `static link head;`)

Stack Implementation With Linked Lists

stacklist.c (cont)

```
link NEWnode(int item, link next) {
  link x = malloc(sizeof *x);
  assert(x != NULL);
  x->item = item; x->next = next;
  return x;
}
void STACKpush(int item) {
  link x = NEWnode(item, head);
  head = x;
}

int STACKpop(void) {
  int item = head->item;
  link x = head->next;
  free(head);
  head = x;
  return item;
}
```

- allocate memory and initialize new node (→ `NEWnode`)
- insert at beginning of list (→ `STACKpush`)
- give memory back to system (→ `free(head);`)
- `free` is opposite of `malloc`

Compilation

Switch implementation without changing interface or client.

```
%gcc client.c stacklist.c
```

OR

```
%gcc client.c stackarray.c
```

Implementing Stacks: Arrays vs. Linked Lists

We can implement a stack with either array or linked list.
Which is better?

Array
- Requires upper bound MAX on stack size.
- Uses space proportional to MAX.

Linked List
- No need to know stack size ahead of time.
- Requires extra space to store pointers.
- Dynamically allocating memory with `malloc` slows down code.

Conclusions

Whew, lots of material in this lecture!

Pointers are useful, but confusing.

Study these slides and carefully read relevant material.