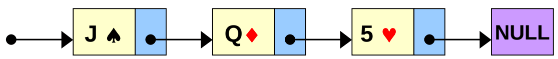
Lecture P8: Pointers and Linked Lists

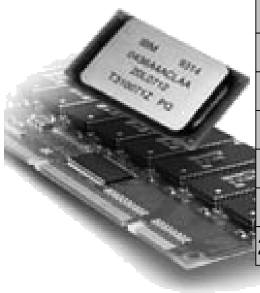


Pointer Overview

Basic computer memory abstraction.
- Indexed sequence of bits.
- Address = index.

Pointer = VARIABLE that stores memory address.

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



addr	value
0	0
1	1
2	1
3	1
4	0
5	1
6	0
7	0
8	1
9	0
10	1
. . .	. . .
256GB	1

Pointers in TOY

Variable that stores the value of a single MEMORY ADDRESS.
- In TOY, memory addresses are 00 – FF.
  - indirect addressing: store a memory address in a register
- Very powerful and useful programming mechanism.
- Confusing and easy to abuse!

Address	D0	D1	D2	..	D9	DA	DB	..	E5	E6	E7
Value	1	9	E5	..	7	0	00	..	3	5	D9

Memory location D2 stores a "pointer" to another memory location (E5) of interest.

Pointers in C

C pointers.
- If x is an integer:
  - &x is a pointer to x (memory address 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: function that swaps values of two integers.

A first attempt:

only swaps copies of x and y

badswap.c

```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: function that swaps values of two integers.

Now, one that works.

changes value stored in memory address for x and y

swap.c

```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;
}
```


Linked List Overview

Goal: deal with large amounts of data.

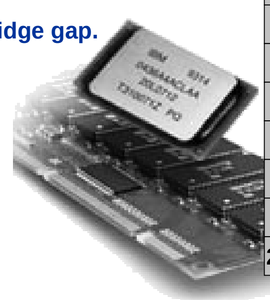
- Organize data so that it is easy to manipulate.
- Time and space efficient.

Basic computer memory abstraction.

- Indexed sequence of bits.
- Address = index.

Need higher level abstractions to bridge gap.

- Array.
- Struct.
- LINKED LIST
- Binary tree.
- Database.
- . . .



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3	1
4	0
5	1
6	0
7	0
8	1
9	0
10	1
. . .	. . .
256GB	1

Linked List

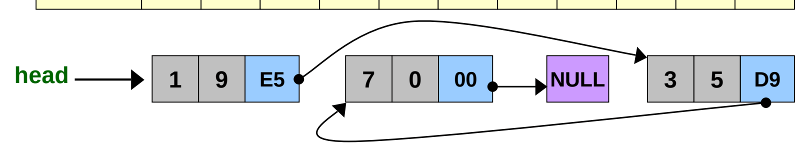
Fundamental data structure.

- 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.

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

- Assume linked list starts in location D0.

Address	D0	D1	D2	..	D9	DA	DB	..	E5	E6	E7
Value	1	9	E5	..	7	0	00	..	3	5	D9



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Address	D0	D1	D2	..	D9	DA	DB	..	E5	E6	E7
Value	1	9	E5	..	7	0	00	..	3	5	D9

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.

Lesson: know space and time costs.

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

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`.
- Include `struct` field for coefficient and exponent.

How to specify links.

- Include `struct` field for POINTER to next linked list element.

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.

memory address of next node

initialize data

link up nodes

define node to store two integers

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;
}
```

Linked List for Polynomial

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

- Statically, using nodes.
- Dynamically using links.

initialize data

allocate enough memory to store node

link up nodes of list

Study this code: tip of iceberg!

poly2.c

```
#include <stdlib.h>

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

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

  x = malloc(sizeof *x);
  x->coef = 1; x->exp = 9;
  y = malloc(sizeof *y);
  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;
}
```


Better Programming Style

Write separate function to handle memory allocation and initialization.

check if malloc fails

Initialize pointers to NULL

poly3.c

```
#include <stdlib.h>

link NEWnode(int c, int e, link n) {
  link x = malloc(sizeof *x);
  if (x == NULL) {
     printf("Out of memory.\n");
     exit(EXIT_FAILURE);
  }
  x->coef = c; x->exp = e; x->next = n;
  return x;
}

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


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  STACKisempty(void);
void STACKpush(int item);
int  STACKpop(void);
void STACKshow(void);
```

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

client.c

```
#include "STACK.h"

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


Stack Implementation With Linked Lists

stacklist.c

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

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

static link head = NULL;

void STACKinit(void) {
   head = NULL;
}

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

standard linked list data structure

`static` to make it a true ADT

head points to top node on stack

Stack Implementation With Linked Lists

stacklist.c (cont)

allocate memory and initialize new node

insert at beginning of list

```
link NEWnode(int item, link next) {
  link x = malloc(sizeof *x);
  if (x == NULL) {
     printf("Out of memory.\n");
     exit(EXIT_FAILURE);
  }
  x->item = item; x->next = next;
  return x;
}
void STACKpush(int item) {
  head = NEWnode(item, head);
}
```


Stack Implementation With Linked Lists

stacklist.c (cont)

```
int STACKpop(void) {
   int item;
   if (head == NULL) {
      printf("Stack underflow.\n");
      exit(EXIT_FAILURE);
   }
   item = head->item;
   link x = head->next;
   free(head);
   head = x;
   return item;
}

void STACKshow(void) {
   link x;
   for (x = head; x != NULL; x = x->next)
      printf("%d\n", x->item);
}
```

free is opposite of `malloc`: gives memory back to system

traverse linked list

Implementing Stacks: Arrays vs. Linked Lists

We can implement a stack with either array or linked list, and switch implementation without changing interface or client.

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

OR

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

Which is better?

- Array
  - ✎
  - ✎
- Linked List
  - ✎
  - ✎
  - ✎

Conclusions

Whew, lots of material in this lecture!

Pointers are useful, but confusing.

Study these slides and carefully read relevant material.

Lecture P8: Extra Slides

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;
}
```

on arizona, int is 32 bits (4 bytes) ⇒ 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	..

Pointers and Arrays

Just to stress that `a[i]` really means `*(a+i)`:

`2[a] = *(2+a) = 24`

This is legal C, but don't ever do this at home!!!

integer (on arizona) takes 4 bytes ⇒ 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

Pass array to function.

- Pointer to array element 0 is passed instead.

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

passes &a[0] = D000 to function

Why Pass Array as Pointer?

Advantages.

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]

Passing Arrays to Functions

Many C programmers use `int *b` instead of `int b[]` in function prototype.

- **Emphasizes that array decays to pointer when passed to function.**

average function

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

an equivalent function

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