Computer Systems

Lecture 14

Linked Lists

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Outline

- Linked lists
- Basic operations on lists
- Traversing a list
- Comparing lists and arrays
- Abstract data type

Review of pointers

- p := &x p is a pointer to x

```
lea R5,x[R0]          ; R5 := &x
```

- y := *p y is the value that p points to

```
load R6,0[R5]         ; R6 := *R5
```

Linked lists: Nodes

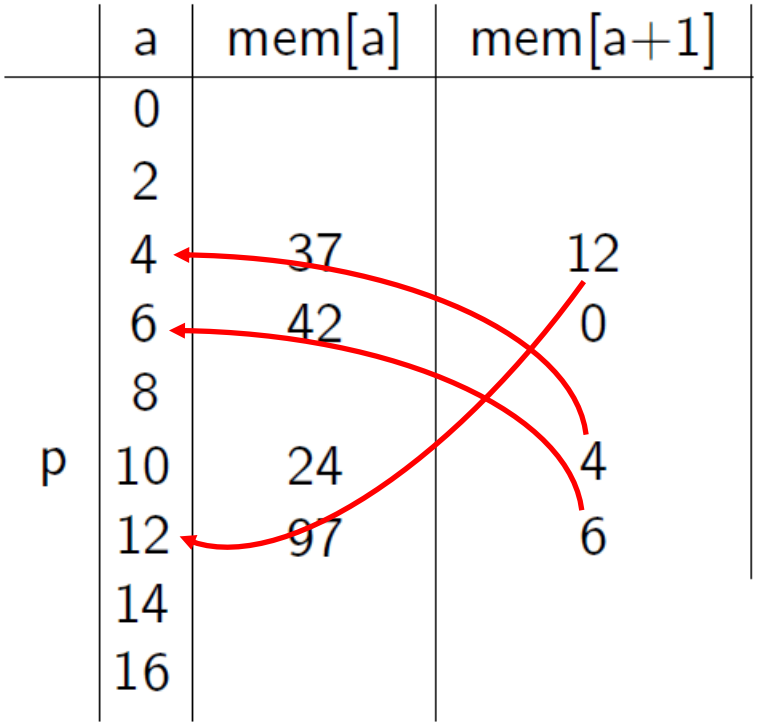
- A linked list consists of a linear chain of nodes
- A node is a record with two fields
  - value is a word containing useful information, the content of the node (e.g. an integer, character, or even a pointer to something else)
  - next is a word containing a pointer to the next node in the list
- The last node in the list has a special value *nil* in the next field
- nil is represented by 0
  - You can't have a pointer to memory location 0 (that's where the program starts, so you wouldn't want that anyway)

Accessing the fields of a node

- Suppose p is a pointer to a node

```
load R1,p[R0]        ; R1 := p
load R2,0[R1]        ; R2 := (*p).value
load R3,1[R1]        ; R3 := (*p).next
```

Representing a linked list



- p = 10, and the list p = [24, 37, 97, 42]

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Basic operations on lists

- Three key operations
  - Is a list p empty?
  - What's the value in a node?
  - What's the next node

- The following code assumes that all the pointer variables (p, q) are in memory, so they must be loaded and stored

- In practice, we often keep the pointers in registers so you don't need all those loads and stores

Is list p empty?

- Nil is 0, so the list that p points at is empty iff p=0

- It is unsafe to perform an action on a list p unless p actually points to a node, so this test is commonly needed

```
load R1,p[R0]
cmpeq R2,R1,R0
jumpt R2,pIsEmpty[R0]
; No, p is not empty
...
...
pIsEmpty
; Yes, p is empty
```

Get value in node that p points at: x := *p.value

- x := *p.value

- This is safe to do only if p is not empty

- The value field of a node is at offset 0 in the node record

```
load R1,p[R0]          ; R1 := p
load R2,0[R1]          ; R2 := *p.value
store R2,x[R0]         ; x := *p.value
```

Get pointer to next node in a list: q := *p.next

- q := *p.next
- This is safe to do only if p is not empty
- The next field of a node is at offset 1 in the node record

```
load R1,p[R0]        ; R1 := p
load R2,1[R1]        ; R2 := *p.next
store R2,q[R0]       ; q := *p.next
```

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Traversing a list p

- A while loop is the best looping construct for traversing a list

```
ListSum (p)
        { sum := 0;
          while p /= nil do
            { x := (*p).value;
                    sum := sum + x;
                    p := (*p).next;
            }
```

Search a list p for a value x

- Again, the best looping construct is a while loop

```
ListSearch (p, x)
        { found := False;
          while p /= nil && not found do
            { found := x = (*p).value;
              p := (*p).next;
            }
return found;
        }
```

- This is a good example of the proper use of a while loop
  - The loop works even if the original list p is nil
  - The condition checks for end of data, and also for early completion
  - There is no break/continue statements or goto

cons: constructing a list consing a value to the front

- Suppose p = [23, 81, 62]
- q := cons (56, p)
- After computing q, we have
  - q = [56, 23, 81, 62] q is the same as p but with 56 attached to the front
  - p = [23, 81, 62] p is unchanged

Implementing cons

```
cons (x, p)
        { q := newnode ();
          (*q).value := x;
          (*q).next := p;
          return q;
        }
```

- No change is made to p, or to the node p points to
- A new node is allocated and set to point to p
- A pointer to the new node is returned
- A function like cons is called a *pure function* (produces a new result but does not modify its arguments)

Getting a new node from avail list

```
if avail = nil
        then { error "fatal error: out of heap" }
        else { newnode := avail;
                 avail := (*avail).next;
                 return newnode;
               }
```

Inserting a node with x where p points

```
r := newnode ();
(*r).value := x;
(*r).next := (*p).next;
(*p).next := r;
```

- Notice that we can insert x after the node that p points to
- But we cannot insert x before that node
- It's common, in list algorithms, to have two pointers moving along through the list, one lagging an element behind the other, to make insertion posible
  - Trailing pointer

List header

- Suppose we have a list p and a value x
- We want to insert x into the list p at an arbitrary point
- Another pointer q points to the insertion position
  - If q in the middle, we can insert x after the node that q points to
  - The insertion algorithm will change (*q).next
- **Problem**: we cannot insert x at the front of the list
- **Solution**: don't use an ordinary variable for p, make a *header node*
  - The next field points to the list
  - The value field is not used

Deleting a node

- Need a pointer p into the list
- The node after p will be deleted
- Just change (*p).next to skip over the next node, and point to the one after
- The node being deleted should be returned to the avail list, so it can be reused

Code for deleting a node

- If p points to a node, delete the node after that, assuming it exists

```
delete (p)
        { if p /= nil
          then { q := (*p).next;
                 if q /= nil
                   then { (p*).next := (*q).next;
                          (*q).next := avail;
                           avail := q;
                        }
               }
}
```

- We can't delete the node p points to, only the following node q points at
- If you know that p cannot be nil, the first test can be omitted
- We need to check whether q = nil; if it is, there's no node to delete
- It doesn't matter whether (*q).next is nil

Space leaks

- If you return a deleted node to the avail list, it can be reused
- If you don't, this node becomes inaccessible
  - It doesn't hold useful data, yet it can't be allocated
- This is a bug in the program (you can run out of memory)
- Over time, as a program runs, more and more nodes may become inaccessible: a space leak

Memory management

- It's a bug if you delete a node that contains useful data
- It's a bug if you don't delete a node that doesn't contain useful data
- With complicated data structures, this can be difficult
- A common solution is garbage collection
  - The program doesn't explicitly return nodes to the avail list
  - Periodically, the garbage collector traverses all data structures and marks the nodes it finds
  - Then the GC adds all unmarked nodes to the avail list

Sharing and side effects

- Suppose p = [6, 2, 19, 37, 41]
- Traverse a few elements, and set q to point to the 19 node
- Now q = [19, 37, 41] and p is unchanged
- Then delete the second element of q, the result is
  - q = [19, 41]
  - p = [6, 2, 19, 41] Modifying q has also modified p
- This is called a side effect
- Sometimes you want this to happen, sometimes not, so be careful!

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Comparing lists and arrays

- Lists and arrays are two different kinds of data structure that contain a sequence of data values
- How do you decide which to use?
- Consider the properties of lists and arrays, and the needs of your program
- And there are many other data structures to choose from, which you'll encounter as you learn computer science

Accessing elements

- Direct access to an element
  - **Array**: gives direct access (“random access”) to element with arbitrary index i
  - **List**: gives direct access only to an element you have a pointer to; random access is inefficient

- Traversal
  - **Array**: initialise i to 0
    - repeatedly set i := i+1; terminate when i ≥ n (purpose of a for loop)
  - **List**: initialize p to point to the list
    - repeatedly set p := (*p).next; terminate when p = nil

Usage of memory

- Memory needed per element
  - **Array**: need just the memory required for the element (typically a word)
  - **List**: need a node for each element, which also requires space for the next pointer (typically a word)
  - So typically, an array with n elements needs n words, while a list requires 2 × n words

- Flexibility
  - An array has fixed size and needs to be allocated fully
  - A list has variable size and needs only enough memory to hold its nodes

More general data structures

- We can put several pointer fields in each node, and produce an enormous variety of data structures, tailored for the needs of an application program

- Just a few examples

  - **Doubly linked list**: each node contains two pointers, one to the previous node and one to the next
    - Allows traversal both directions

  - **Circular list**: there is no “last” node where next=nil, instead every node points to the next node, and the list loops back to itself
    - There is no “first” or “last” node

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Abstract data type

- A stack is an abstract data type
  - **Idea**: define the type by the operations it supports, not by the code that implements it
  - There may be different implementations of an ADT, and which implementation is best may depend on the application using it

- The stack ADT is defined by the operations it supports: push, pop

- There are several completely different ways to implement a stack
  - We have already seen how to implement a stack with an array
  - We can also do it with a linked list

Linked list implementation of stack

- A linked list gives easy access to the front of the list, and a stack gives easy access to the top of the stack
- Represent Empty stack as nil
- Push x is implemented by stack := cons (x, stack)
- Pop x is implemented by stack := (*stack).next

Array representation of stack

- We can implement a stack using an array
- There is a variable *stLim* which gives the size of the array
  - This is the limit on the maximum number of elements that can be pushed
- There is a variable *stTop* that gives the current number of elements in the stack

Relationship between arrays and stacks

- Array
  - A container that holds many elements
  - Each element has an index (which is an integer)
  - You can access any element x[i]
  - You can access the elements in any order

- Stack
  - A container that holds many elements
  - You can only access the top element, and don't need to know its index
  - You can (and must) access the elements in *Last In First Out* order

Pushing x onto a stack

```
; push the x onto the stack
; stack[stTop] := R1      ; stTop := stTop + 1
push load R1,x[R0]        ; R1 := x
load R2,stTop[R0]         ; R2 := stTop
store R1,stack[R2]        ; stack[stTop] := x
lea R3,1[R0]              ; R3 := constant 1
add R2,R2,R3              ; R2 := stTop + 1
store R2,stTop[R0]        ; stTop := stTop + 1
```

Pop a stack, returning x

```
; pop the stack, store top element into x
; stTop := stTop – 1                ; x := stack[stTop]
pop load R2,stTop[R0]               ; R2 := stTop
lea R3,1[R0]                        ; R3 := constant 1
sub R2,R1,R3                        ; R2 := stTop - 1
load R1,stack[R2]                   ; R1 := stack[stTop-1]
store R1,x[R0]                      ; x := stack[stTop-1]
store R2,stTop[R0]                  ; stTop := stTop - 1
```

Issues with simplest implementation

- It doesn't check for errors!
  - If push is called when stack is full, data will be written outside the array
  - If pop is called when stack is empty, a garbage result will be returned

- Either of these errors may cause the program to get wrong answers or crash

Robust software

- Fragile software will respond to a minor problem by going haywire
  - Might crash, or produce wrong answers

- Robust software checks for all errors and does something appropriate
  - A minor problem doesn't turn into a major one

Error checking and error handling

- Software should not assume everything is ok (it should check for errors)
  - push (x) when the stack is full
  - x := pop () when the stack is empty
- If an error is detected, the error must be handled
- There are many approaches
  - Produce a message and terminate the program
  - Return an error code to the calling program and let it decide what to do
  - Throw an exception, which will interrupt the calling program, and invoke its error handler
- For simplicity, we will terminate the program if an error occurs

Error checking: push

- If the stack is full, there is no space to store the new element, so push fails

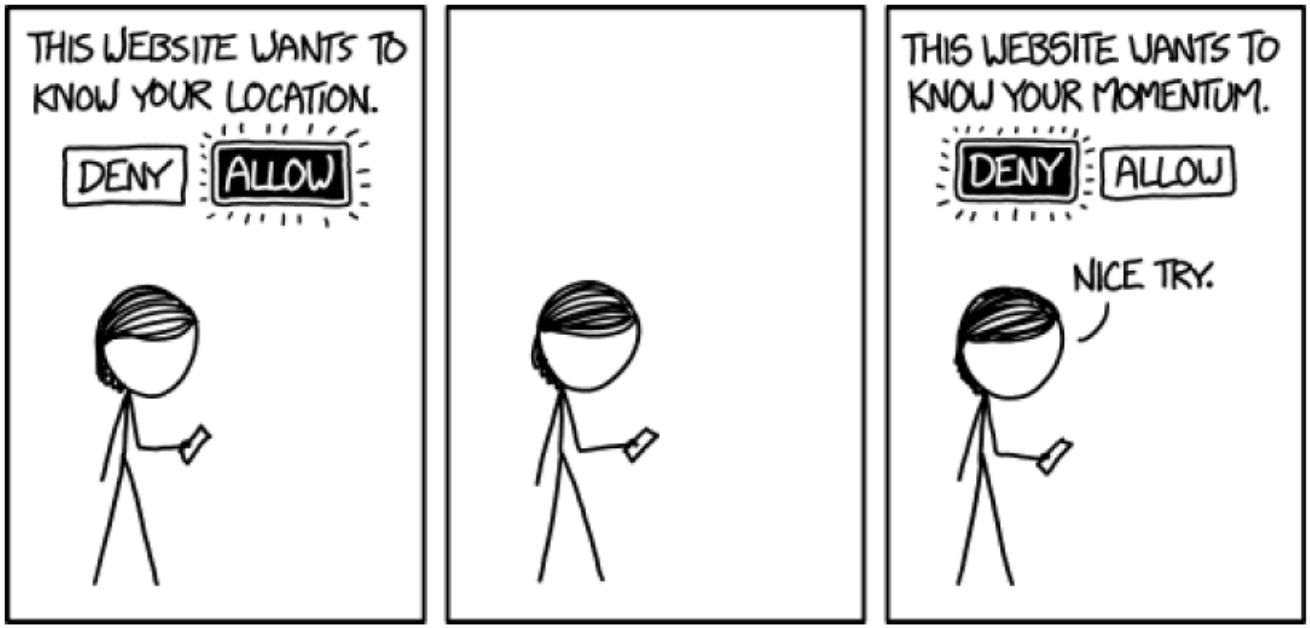
```
; push (v)
; if stTop >= stLim
; then
; terminate because the stack is full: cannot push
; else
; stack[stTop] := v
; stTop := stTop + 1
; return ()
```

Error checking: pop

- If the stack is empty, there is no element to return, so pop fails

```
; v = pop ()
; if stTop == 0
; then
; terminate because the stack is empty: cannot pop
; else
; stTop := stTop - 1
; v := stack[stTop]
; return (v)
```

Location sharing



https://xkcd.com/1473/1