University of Illinois at Urbana-Champaign
Dept. of Electrical and Computer Engineering

ECE 220: Computer Systems & Programming

Containers and Iterators

A Container Holds Other Data Structures

What's a container?
- a **data structure**
- **containing** other **data structures**
- with specific access capabilities.

Examples include
- linked lists,
- heaps (the type used for MP9), and
- dynamically-sized arrays.

Example: a Singly-Linked List Containing "Things"

For simplicity,
- consider a **singly-linked list**
- **containing "things."**

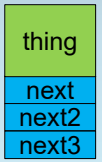
How do the list elements hold "things?"

Adding Containers to Structures Implies More Code

When we studied lists,
- we **added a `next` field**
- to a data structure
- **to create a linked list**.

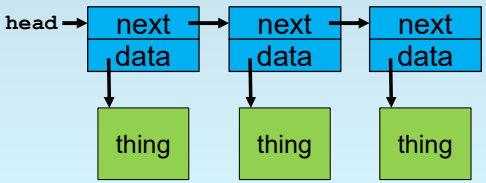
And said: just
- **add more** fields
- **to create multiple lists**.

But **to do so**, we must **write code for each list separately**.

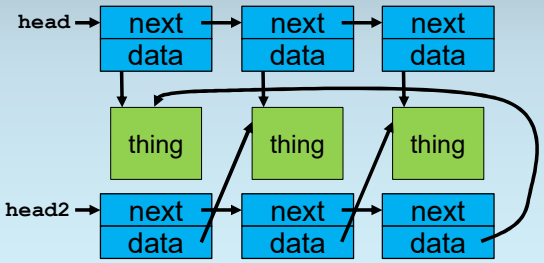


List Elements Can Point to the "Things"

To **avoid writing** list **code repeatedly**,
- we can **create a list element** structure
- **with** a **data pointer** (**`void*`**),
- then build a list with list nodes.



Other Lists Can Point to the Same Set of "Things"



For another list, use more list elements!

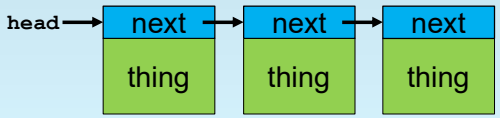
Extra Level of Indirection: Simpler Code, But Slower

Using an **extra level of indirection**
- (a pointer to a structure with a pointer)
- implies that we **write the list code once**
- (all lists look the same to the code!)
- but use requires **more memory accesses**.*

*Also note that some container properties may be affected. Removal from a doubly-linked list built in this way is not fast if one has only a "thing" pointer, for example.

Simpler Code Can be Achieved in Another Way

There is another option:
- **to write** the list **code once**,
- the **`next` field must point to** a **list element** structure,
- but that structure may be part of a larger structure.



Including List Element is Faster, But Allows Just One List

In other words,
- **create a list element** structure
- **consisting of a `next` field** (only), and
- **include** a **list element** structure
- **as first element of** the **"thing"** structure.

For list code, a "thing" is just a list node.

List nodes can be turned into "things" (the address is the same)!

But **can only have one list** for any "thing."

Example: Cyclic, Doubly-Linked List with a Sentinel

Let's build an **example container**:
- **cyclic, doubly-linked list with a sentinel**
- **using list element inclusion** (rather than extra pointers).

In particular,
- a **`double_list_t`** includes pointers to **`next`** and **`prev`** **`double_list_t`**'s, and
- first field of "thing" is a **`double_list_t`**.

A List Node is Simple: Just Two Pointers

```
typedef struct double_list_t
               double_list_t;
struct double_list_t {
    double_list_t* prev;
    double_list_t* next;
};
```

How do we initialize a list?

List Variables Can be Statically or Dynamically Initialized

List variables can be **initialized statically**:

```
// this variable is the sentinel
static double_list_t my_list =
    {&my_list, &my_list};
```

But **dynamically-allocated lists** must be **initialized at runtime**.

Initialize Dynamically by Pointing Sentinel to Itself

Let's write a routine for initialization:

Given a pointer to the **head** of the list,

```
void dl_init (double_list_t* head)
{
    head->prev = head->next = head;
}
```

point **prev** and the **next** fields back to the **head**.

List Insertion Requires the Head and the New Element

To insert an element into a list, we **need**
- a **pointer** to the **list head** and
- a **pointer** to the **new element**.

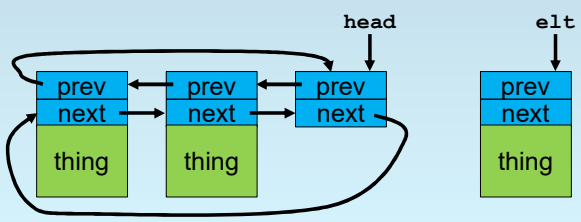
For example, we might write:

```
void dl_insert (double_list_t* head,
                double_list_t* elt);
```


Structures for Insertion Include List and Element

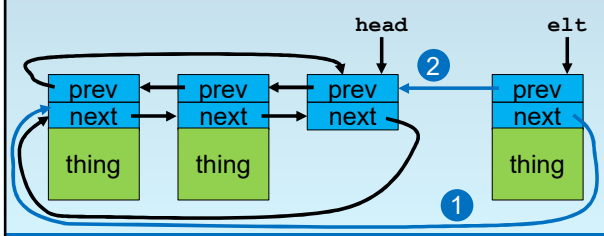
```
void dl_insert (double_list_t* head,
                double_list_t* elt);
```

So we have…



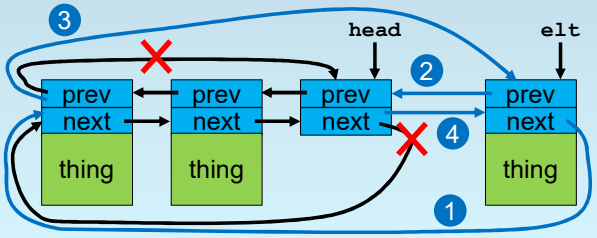
First Two Insertion Steps Change New Element

```
elt->next = head->next;  // step 1
elt->prev = head;        // step 2
```



Second Two Insertion Steps Change List

```
head->next->prev = elt;  // step 3
head->next = elt;        // step 4
```



Complete Code for List Insertion

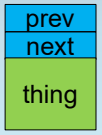
Together, we have:

```
void dl_insert (double_list_t* head,
                double_list_t* elt)
{
    elt->next = head->next;
    elt->prev = head;
    head->next->prev = elt;
    head->next = elt;
}
```


The "Thing" Must Have a `double_list_t` Field First

But what IS the "thing"?

Any data structure, as follows:




```
struct thing_t {
    double_list_t dl;
    // the rest of the structure
};
```

`double_list_t` must be first in structure.

To Insert, Use the Address of the `double_list_t` Field

Once we create a list and a thing:

```
double_list_t my_list =
              {&my_list, &my_list};
struct thing_t my_thing;
```

We can insert the thing into the list as follows:

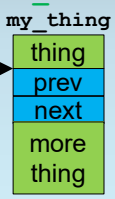
```
dl_insert (&my_list, &my_thing.dl);
```

Same address as `&my_thing`.

Pitfall: Not Putting the `double_list_t` First

What happens if the `double_list_t` is not first in "thing?"

`&my_thing->dl` points here.

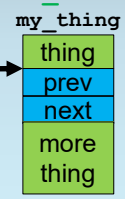



```
struct thing_t {
    // some stuff
    double_list_t dl;
    // the rest of the structure
};
```


`double_list_t` MUST be First in Thing!

What happens if the `double_list_t` is not first in "thing?"

`&my_thing->dl` points here.



Cannot convert `double_list_t*` to `struct thing_t*` (need to subtract unknown amount from the pointer.).

List Removal Requires Only the Element to Remove

To remove an element from a list, we **only need** a **pointer** to the **element** to be removed.

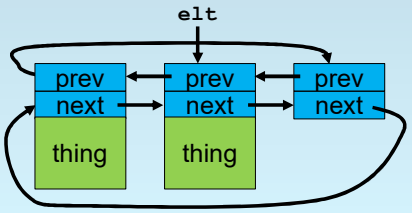
For example, we might write:

```
void dl_remove (double_list_t* elt);
```


Structures for Removal Include Only the Element

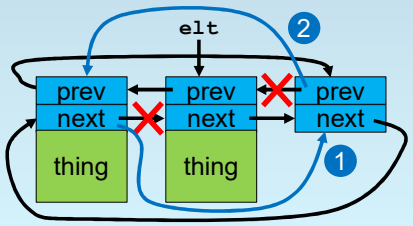
```
void dl_remove (double_list_t* elt);
```

So we have…



Two Steps for Removal from List

```
elt->prev->next = elt->next;//step 1
elt->next->prev = elt->prev;//step 2
```



Can Also Provide Other Access Methods

We can also provide other access methods.

For example, a routine to
find the first element in a list.

```
// Returns a pointer to the first
// element in a list, or NULL for
// an empty list.
void* dl_first
    (double_list_t* head);
```


One Line Needed to Find the First Element in a List

Such a routine is not hard to write:

```
// Returns a pointer to the first
// element in a list, or NULL for
// an empty list.
void* dl_first
    (double_list_t* head)
{
    return (head == head->next ?
            NULL : head->next);
}
```

Is the list empty?

Can We Provide a Way to Iterate Over "Things"?

What about iterating over the list elements?

Let's say that we want
- to **execute some code**
- **for every "thing"** in a list.

Again, we want to
- **avoid exposing** the **details** of our list implementation, and
- **avoid requiring** many **copies of iteration control** code.

Use a Callback for Iteration

Can we write a function to perform iteration?

Yes, by placing the code to execute for each "thing" in a callback!

Arguments to the Callback: `void*` and `void*`

What signature should we use for the callback?

First, we **need**
- a **pointer to** the **"thing."**
- Let's use a **`void*`**.

To allow specialization, we also need
- a **pointer to other arguments**,
- also a **`void*`**.

Return Value Type `void` Acceptable for Pure Iteration

What should the callback return?

If all we want **to** do
- is **iterate over all things**,
- return type **`void` is fine**.

Iteration Can Be Used for Many Purposes

What else might we want to do?

1. **Find a specific "thing"** (and possibly remove it from the list).
2. **Remove a set of "things"** from the list (remove and keep going).
3. **Free a set of "things"** from the list (remove, free, and keep going).

Design to Allow Changes to List During Callback

Here we have design choices.

Our choice:

- one **can safely change the list** in the callback function,
- **EXCEPT** that one **cannot remove the "thing"** passed to the callback from the list.

(The alternative choices can be confusing to use.)

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Callback Returns a Number Saying What to Do

So, again, what should the callback return?

An enumerated constant!

Let's call it **`dl_execute_response_t`**.

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Meanings of Possible Callback Return Values

```
typedef enum {
    DL_CONTINUE,
    DL_STOP_AND_RETURN,
    DL_REMOVE_AND_CONTINUE,
    DL_REMOVE_AND_STOP,
    DL_FREE_AND_CONTINUE
} dl_execute_response_t;
```

Keep going.

Return this "thing."

Remove "thing" and continue with next one.

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Meanings of Possible Callback Return Values

```
typedef enum {
    DL_CONTINUE,
    DL_STOP_AND_RETURN,
    DL_REMOVE_AND_CONTINUE,
    DL_REMOVE_AND_STOP,
    DL_FREE_AND_CONTINUE
} dl_execute_response_t;
```

Remove "thing" and return it.

Free "thing" and continue with next one.

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Iteration Callback Takes Two `void*`, Returns a Number

And here's the definition for the callback function:

```
typedef dl_execute_response_t
        (*dl_execute_func_t)
        (void* dl, void* arg);
```


Iteration Requires Three Arguments

Now we can also write the function signature for iteration:

```
void* dl_execute_on_all
     (double_list_t* head,
      dl_execute_func_t func,
      void* arg);
```

Pointer to head of list.

Pointer to callback function.

Argument passed to (all) callback invocations.

Iteration Returns a Pointer to a "Thing"

Now we can also write the function signature for iteration:

Returns a pointer to a "thing."

```
void* dl_execute_on_all
     (double_list_t* head,
      dl_execute_func_t func,
      void* arg);
```


Local Variables for our Iteration Function

And here's the function:

```
double_list_t* dl;
double_list_t* remove;
dl_execute_response_t result;
```

iteration over list elements

element to be removed

result returned from callback

For Every "Thing," Call the Callback and Take Action

```
for (dl = head->next; head != dl;
     dl = dl->next) {

  result = (*func) (dl, arg);

  switch (result) {
```

Loop over all things.

Call the callback function.

Take action based on callback's response.

Cases to Return "Thing" After Possibly Removing It

```
switch (result) {

    case DL_REMOVE_AND_STOP:
        dl_remove (dl);
    case DL_STOP_AND_RETURN:
        return dl;
```

Remove the "thing"…

… and return it! (no **break**)

This case returns "thing" without removing.

Cases to Remove "Thing" and Continue (Maybe Freeing)

```
    case DL_REMOVE_AND_CONTINUE:
    case DL_FREE_AND_CONTINUE:
        remove = dl;
        dl = dl->prev;
        dl_remove (remove);
        if (DL_FREE_AND_CONTINUE ==
            result) {
            free (remove);
        }
        break;
```

Copy "thing" to **remove**.

Loop update reads this element's **next**.

Cases to Remove "Thing" and Continue (Maybe Freeing)

```
    case DL_REMOVE_AND_CONTINUE:
    case DL_FREE_AND_CONTINUE:
        remove = dl;
        dl = dl->prev;
        dl_remove (remove);
        if (DL_FREE_AND_CONTINUE ==
            result) {
            free (remove);
        }
        break;
```

Remove "thing" from list.

If requested, free "thing" (other data can be freed by callback).

DL_CONTINUE Case is Based on Loop

```
        default:
            break;
    }  // end of switch
} // end of loop over "things"
return NULL;
```

DL_CONTINUE handled here.

If loop ends, return NULL.

Code is Available in Lab14

That's all!

The code is part of Lab 14.

