Basics about Data Structures

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Outline

- This topic will describe:
  - Concrete data structures that can be used to store information
  - Basic forms of **memory allocation**
    - Contiguous
    - Linked
    - Indexed
  - **Prototypical examples** of these: arrays and linked lists
  - **Other data structures**:
    - Trees
    - Hybrids
    - Higher-dimensional arrays
  - Finally, we will discuss the run-time of queries and operations on arrays and linked lists

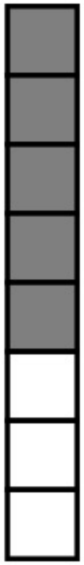
Memory Allocation

- Memory allocation can be classified as either
  - Contiguous
  - Linked
  - Indexed

- Prototypical examples:
  - Contiguous allocation: arrays
  - Linked allocation: linked lists

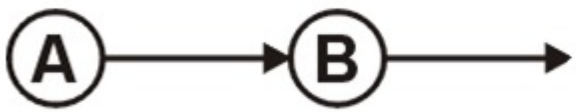
Contiguous Allocation

- An array stores *n* objects in a contiguous space of memory
- Unfortunately, if more memory is required, a request for new memory usually requires copying all information into the new memory



Linked Allocation

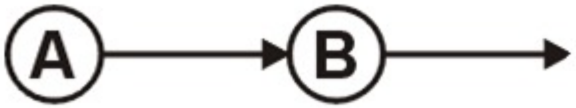
- Linked storage such as a linked list associates two pieces of data with each item being stored:
  - The object itself, and
  - A reference to the next item
    - In C++, the reference is the address of the next node



Linked Allocation

- This is a class describing such a node

```
template <typename Type>
class Node {
    private:
        Type node_value;
        Node *next_node;
    public:
         // ...
};
```



Linked Allocation

- The operations on this node must include:
  - Constructing a new node
  - Accessing (retrieving) the value
  - Accessing the next node

```
Node( const Type& = Type(), Node* = nullptr );
Type value() const;
Node *next() const;
```

- Pointing to nothing has been represented as:

C	NULL
Python	None
Java/C#	null
C++ (old)	0
C++ (new)	**nullptr**
Symbolically	**Ø**

Linked Allocation

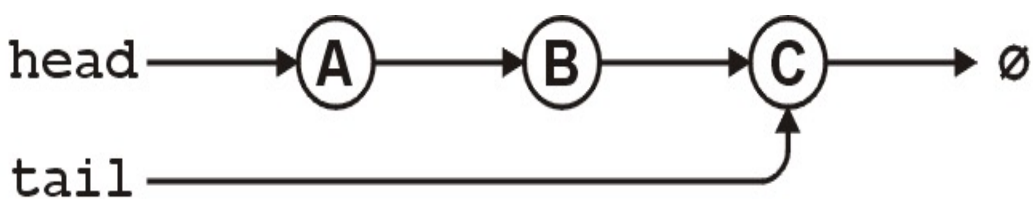
- For a linked list, however, we also require an object which links to the first object
- The actual linked list class must store two pointers
  - A head and tail:

```
Node *head;
Node *tail;
```

- Optionally, we can also keep a count

```
int count;
```

- The `next_node` of the last node is assigned `nullptr`



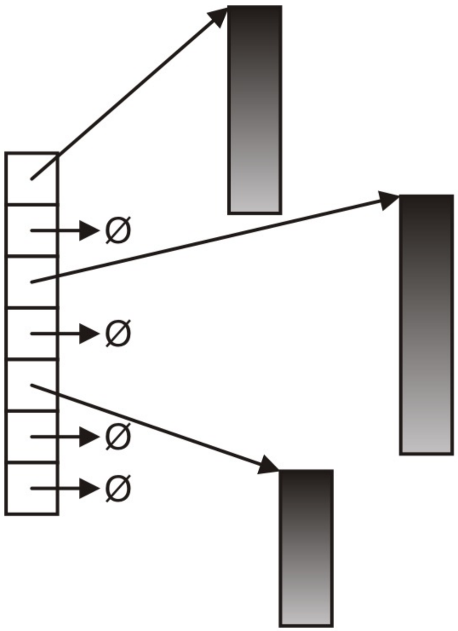
Linked Allocation

- The class structure would be:

```
template <typename Type>
class List {
    private:
        Node<Type> *head;
        Node<Type> *tail;
        int count;
    public:
        // constructor(s)...
        // accessor(s)...
        // mutator(s)...
};
```

Indexed Allocation

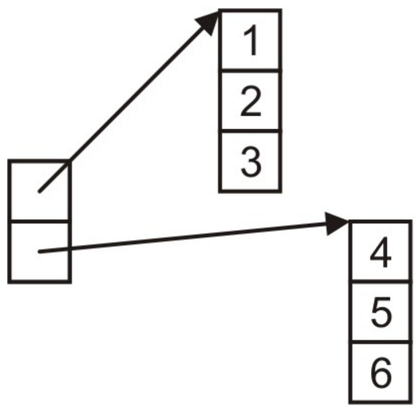
- With indexed allocation, an array of pointers (possibly NULL) link to allocated memory locations

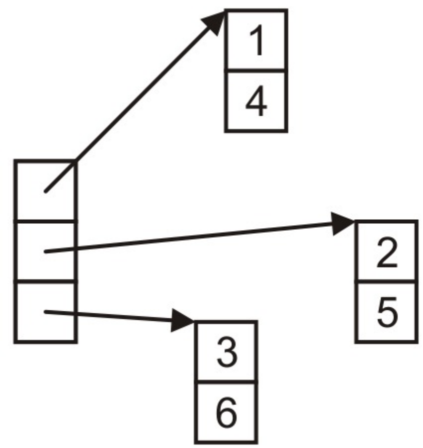


Indexed Allocation

- Matrices can be implemented using indexed allocation:

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$$



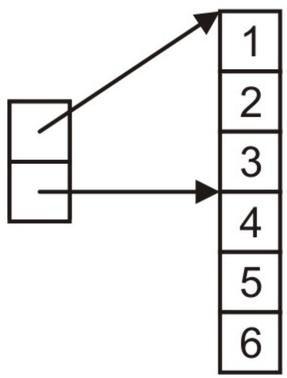


Indexed Allocation

- Matrices can be implemented using indexed allocation
  - Most implementations of matrices (or higher-dimensional arrays) use indices pointing into a single contiguous block of memory

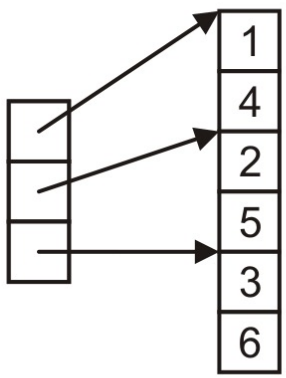
$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$$

Row-major order



C

Column-major order



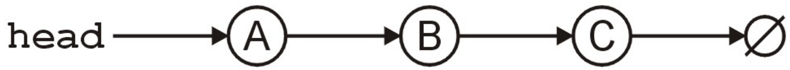
Matlab, Fortran

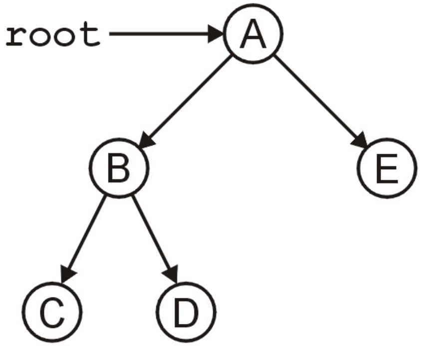
Other Allocation Formats

- We will look at some variations or hybrids of these memory allocations including:
  - Trees
  - Graphs
  - Deques (linked arrays)

Trees

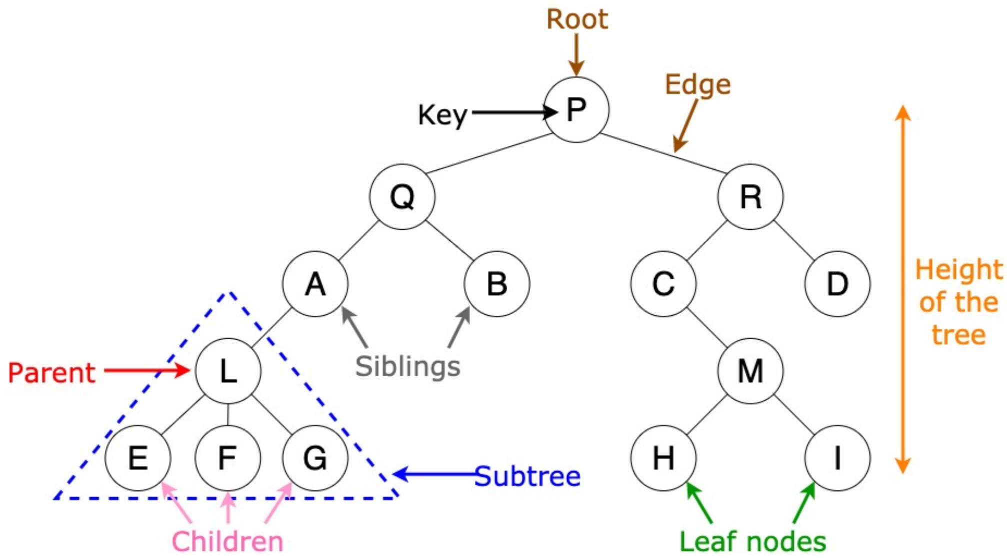
- The linked list can be used to store linearly ordered data
  - What if we have multiple *next* pointers?
- A rooted tree is similar to a linked list but with **multiple next pointers**





Trees

- A tree is a variation of a linked list:
  - Each node points to an arbitrary number of subsequent nodes
  - Useful for storing hierarchical data
  - Useful for storing sorted data
  - Usually we will restrict ourselves to trees where each node points to at most two other nodes

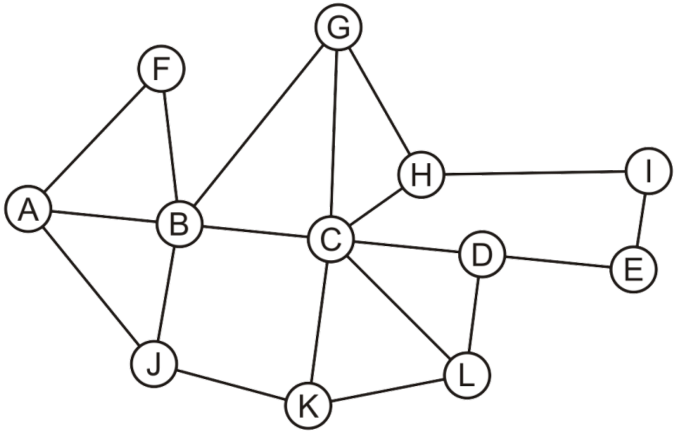


https://towardsdatascience.com/8-useful-tree-data-structures-worth-knowing-8532c7231e8c

Graphs

- Suppose we allow arbitrary relations between any two objects in a container
  - Given n objects, there are $n(n-1)$ possible relations
    - If we allow symmetry, this reduces to $(n^2-n)/2$

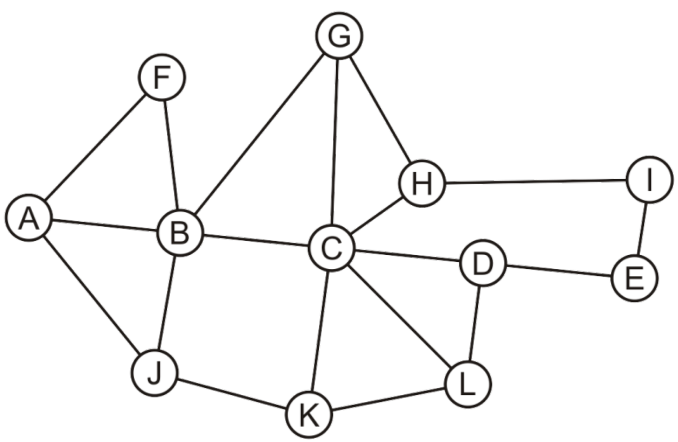
  - For example, consider a network



Graphs in Two-dim. Arrays

Suppose we allow arbitrary relations between any two objects in a container

- We could represent this using **a two-dimensional array**
- In this case, the matrix is *symmetric*

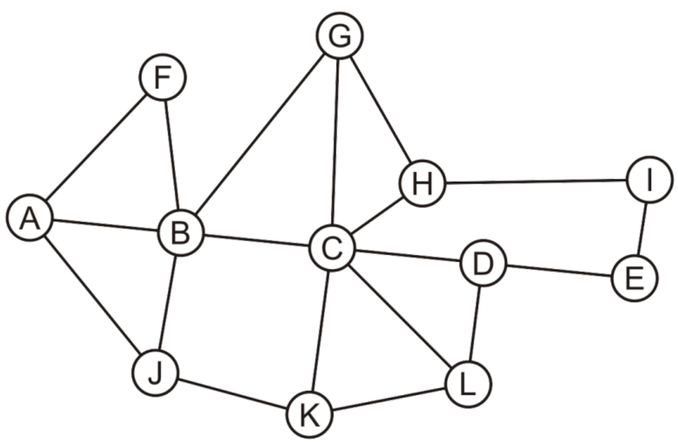


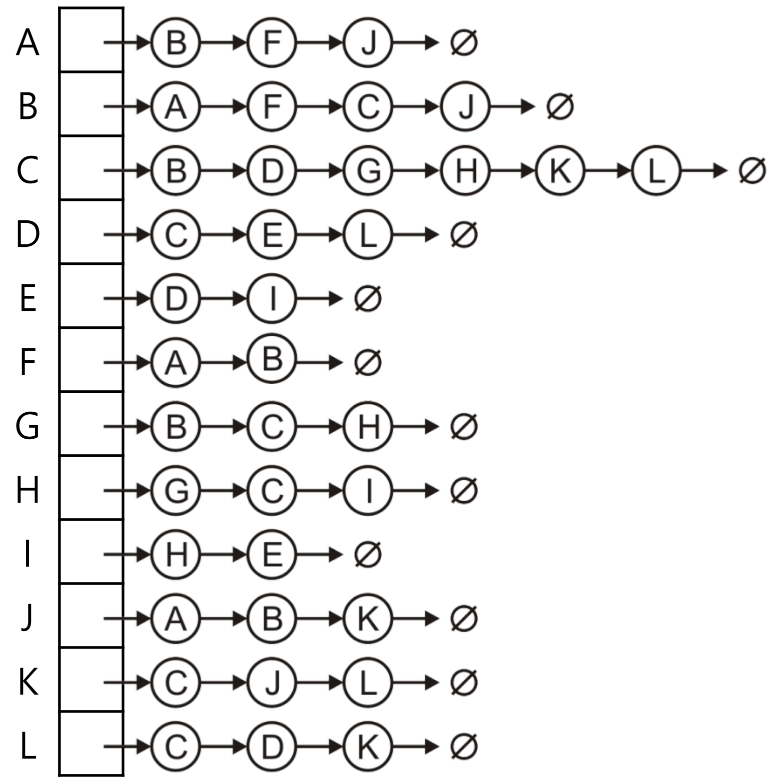
	A	B	C	D	E	F	G	H	I	J	K	L
A		×				×				×		
B	×		×			×	×			×		
C		×		×			×	×			×	×
D			×		×							×
E				×					×			
F	×	×										
G		×	×					×				
H			×				×		×			
I					×			×				
J	×	×									×	
K			×							×		×
L			×	×							×	

Graphs in Array of Linked Lists

Suppose we allow arbitrary relations between any two objects in a container

- Alternatively, we could use a hybrid: **an array of linked lists**





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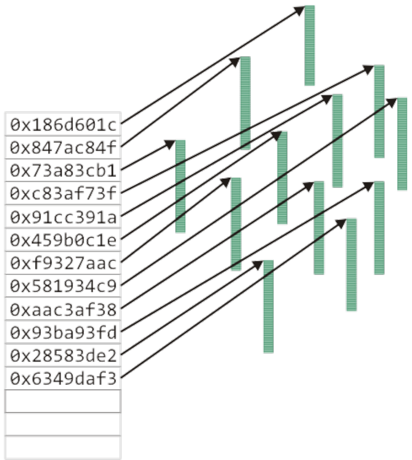
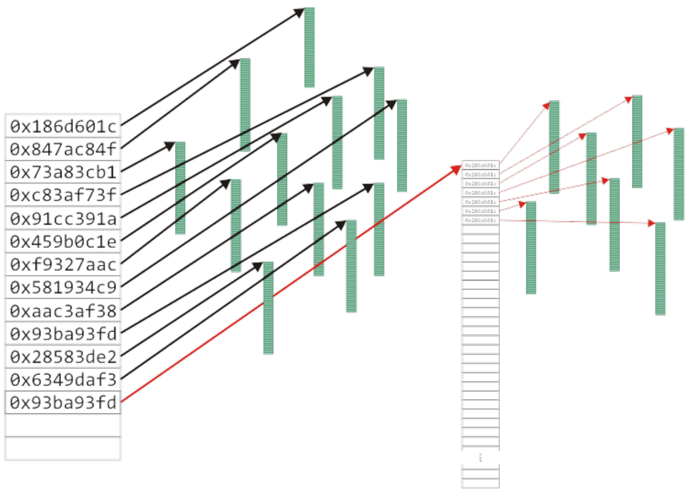
Hybrid data structures

- The UNIX inode (a data structure in UNIX file system that describes a file system object such as a file or a directory) is used to store information about large files for block devices
  - The first twelve entries can reference the first twelve blocks (48 KB)



Hybrid data structures

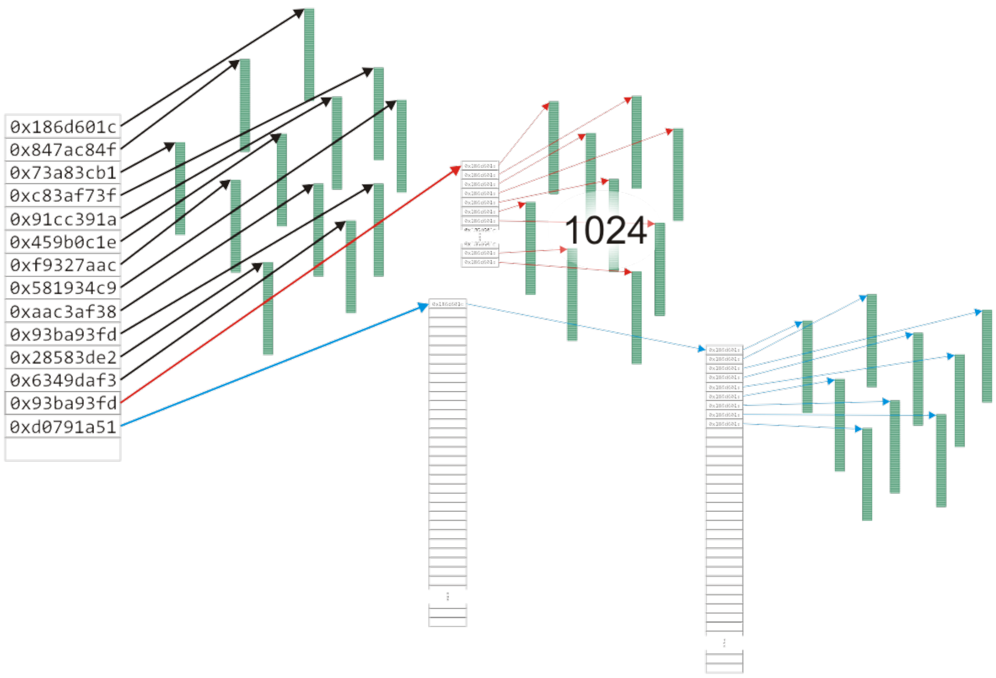
- The Unix inode is used to store information about large files
  - The next entry is a pointer to an array that stores the next 1024 blocks



This stores files up to 4 MB on a 32-bit computer

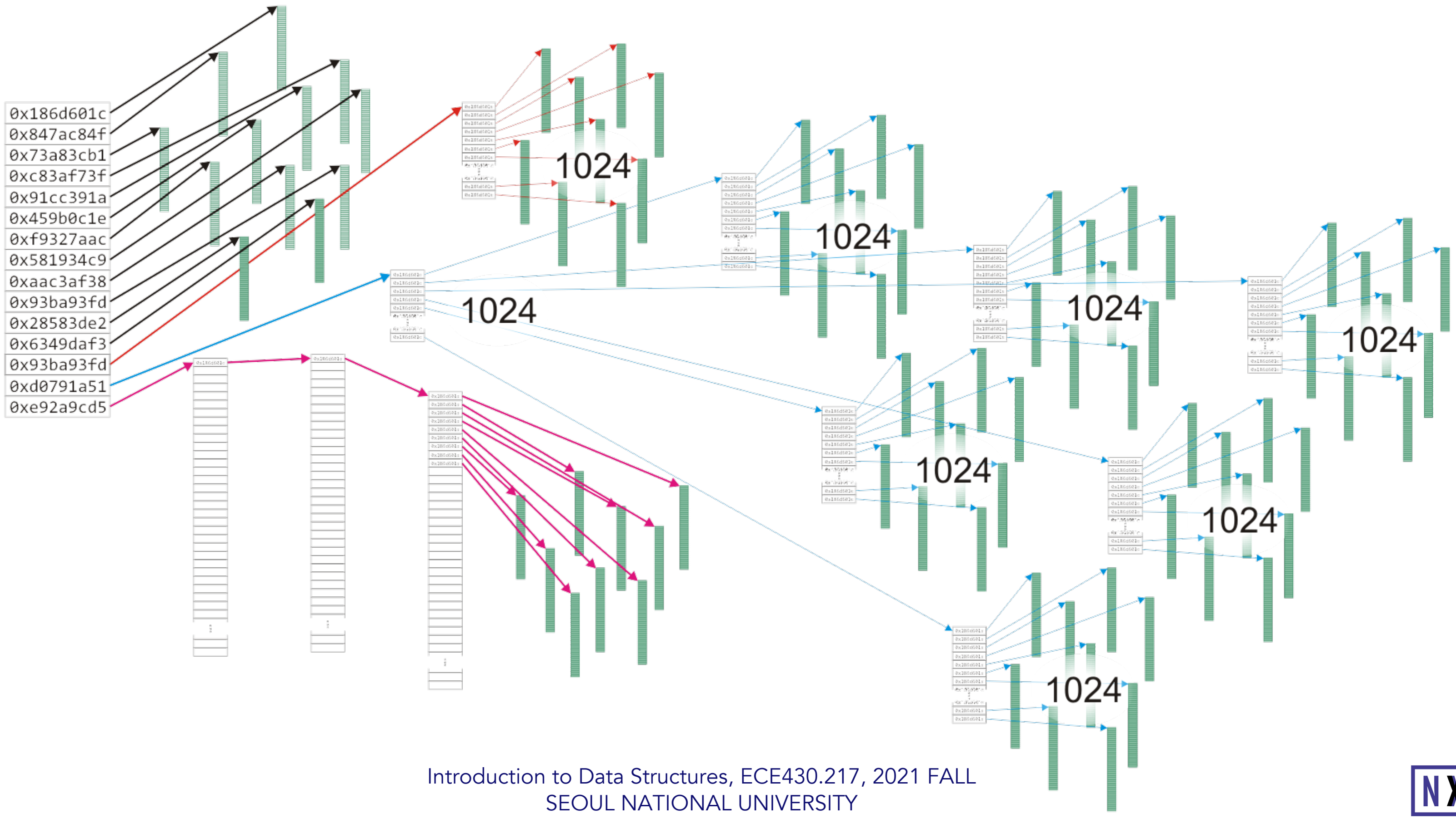
Hybrid data structures

- The Unix inode is used to store information about large files
  - The next entry has two levels of indirection for files up to 4 GB



Hybrid data structures

- The Unix inode is used to store information about large files
  - The last entry has three levels of indirection for files up to 4 TB



Algorithm run times

- Once we have chosen a data structure to store both the objects and the relationships, we must implement the queries or operations as algorithms
  - The Abstract Data Type will be implemented as a class
  - The data structure will be defined by the member variables
  - The member functions will implement the algorithms

- The question is, how do we determine the efficiency of the algorithms?

Operations

- We will use the following matrix to describe operations at the locations within the structure

	Front/1st	Arbitrary Location	Back/nth
Find	?	?	?
Insert	?	?	?
Erase	?	?	?

Operations on Arrays

- Given a sorted array, we have the following run times:

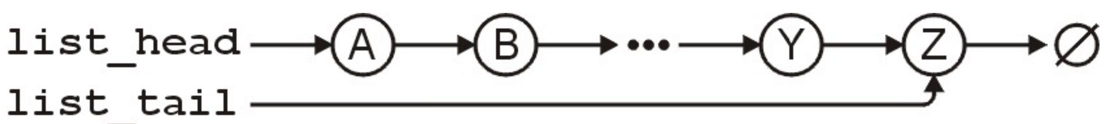
	Front/1st	Arbitrary Location	Back/nth
Find	Good	Good	Good
Insert	Bad	Bad	Good* Bad
Erase	Bad	Bad	Good

* only if the array is not full

Operations on Singly-linked Lists

- For a singly linked list with a head and tail pointer, we have:

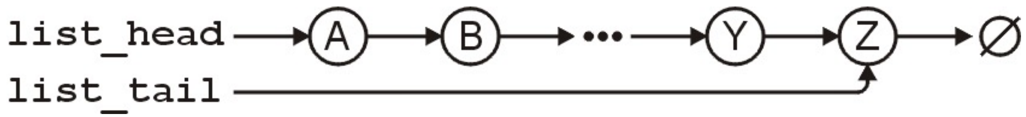
	Front/1st	Arbitrary Location	Back/nth
Find	Good	Bad	Good
Insert	Good	Bad	Good
Erase	Good	Bad	Bad



Operations on Singly-linked Lists

- If we have a pointer to the k^{th} entry, we can insert or erase at that location quite easily

	Front/1st	Arbitrary Location	Back/nth
Find	Good	Good	Good
Insert	Good	Good	Good
Erase	Good	Good	Bad

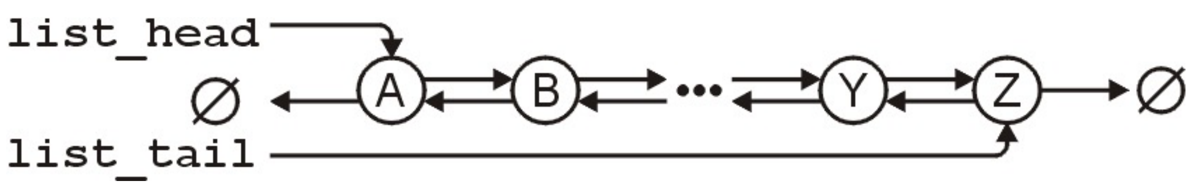


- Note, this requires a little bit of trickery: we must modify the value stored in the k^{th} node
- This is a common coding interview question!

Operations on Doubly-linked Lists

- For a doubly linked list, one operation becomes more efficient:

	Front/1st	Arbitrary Location	Back/nth
Find	Good	Good	Good
Insert	Good	Good	Good
Erase	Good	Good	Good



Next Lecture

- The next topic, asymptotic analysis, will provide the mathematics that will allow us to measure the efficiency of algorithms

- It will also allow us to measure the memory requirements of both the data structure and any additional memory required by the algorithms

Summary

- In this topic, we have introduced the concept of data structures
  - We discussed contiguous, linked, and indexed allocation
  - We looked at arrays and linked lists
  - We considered
    - Trees
    - Two-dimensional arrays
    - Hybrid data structures
  - We considered the run time of the algorithms required to perform various queries and operations on specific data structures:
    - Arrays and linked lists