Core data structures

It’s all about relationships

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Data structures organize data

- Data structures organize, group, or encode relationships between data elements; even a humble list imposes order
- There's a difference between the ***abstract data type*** and the concrete **implementation** (list vs array, dictionary vs hashtable, …)
- Two methods to organize relationships in data:
  - physical adjacency or relative position in memory (RAM)
  - *pointers* (also called *references*)
- Algorithms operate on data structures; e.g., a sorting algorithm operates on a list
- Often algorithms are needed to construct data structures too, but let's get familiar with what these data structures look like and then focus on algorithms that operate on them

Advice on choosing data structures

- Use the simplest data structure you can initially because you never know if that code will survive very long
- Waste processor & memory power before brainpower (if possible)
- There is a trade off between time and space
  - We can often make faster algorithm using more memory
  - It's like driving to the other side of town to save 10% on gas; what are you trying to optimize? time or $$$
- Prep work or a more sophisticated data structure can help
  - E.g., element lookup via: unordered list O(n) vs sorted list O(log n) vs hash table O(1)

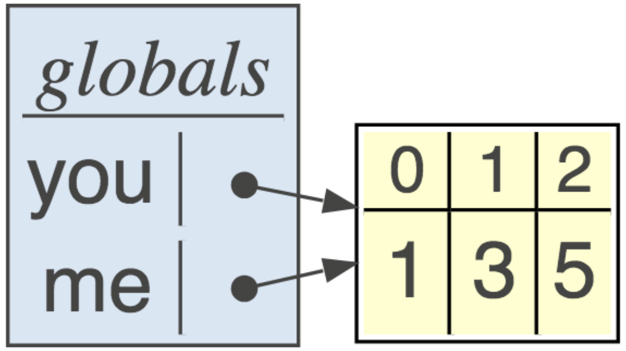
Elemental data in memory (RAM)

- (not disk formats, which we covered in data acquisition MSDS692)
- What's the *type*? Typically int, float, string
- Numbers can be of different sizes; e.g., np.float32, np.float64
- Data *values*: an int can represent a number, signed or unsigned, but can also represent a categorical item such as US state
- We can also use strings for categoricals but it's much less efficient in space, and often time; (encode repeated string copies as ints)
- You can even encode multiple things within a single number, such as using 1105 instead of floor 11, room 05; space vs speed tradeoff
- Data *properties*: e.g., can such values be ordered? Is there a notion of distance between values?

Pointer data type

- A pointer p is implemented as an integer variable that holds a memory address, such as “p = Point(3,4)”; use `id(p)` to get addr
- Python knows variables are actually references to memory locations; the p reference var takes 32 or 64 bits only
- Pointers are also called *references*

```
you = [1,3,5]
me  = you
```



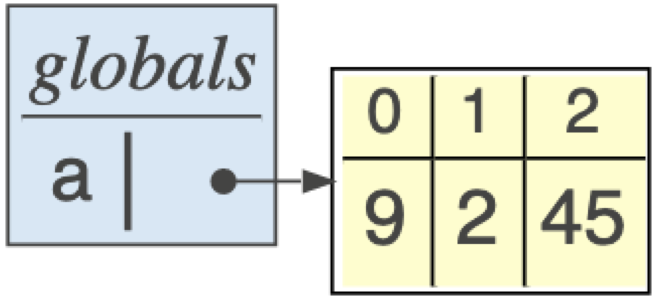
- *Q. How much space does list of strings take?*

  n pointers and space for chars of all n strings

Graphic created with https://github.com/parrt/lolviz

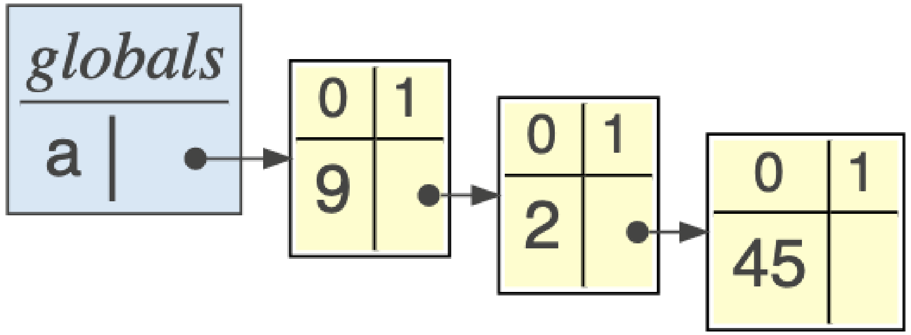
List abstract data type

- *Array* implementation is most common implementation of the *list* abstract data structure
- Lists are ordered but items aren't necessarily sortable
- Arrays use contiguous memory locations to associate items
- Code "a=[9,2,45]" yields a pointer to contiguous block of cells



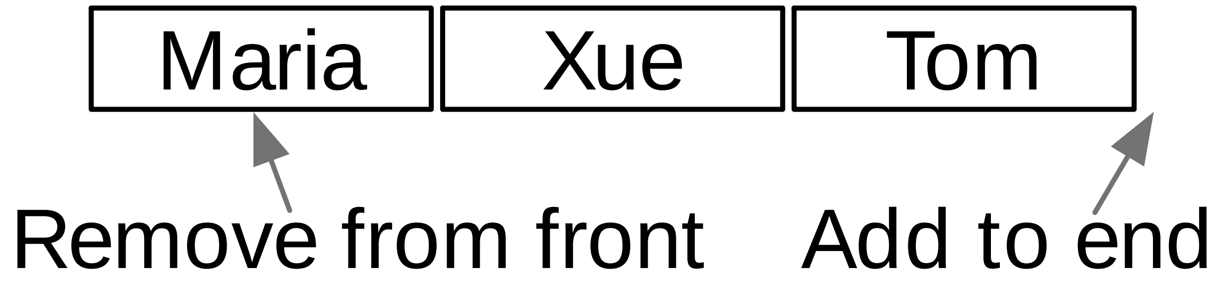
Non-contiguous lists: *linked lists*

- The other way to implement a list data type is with explicit pointers from one element to the next: “a = (9,(2,(45,None)))”



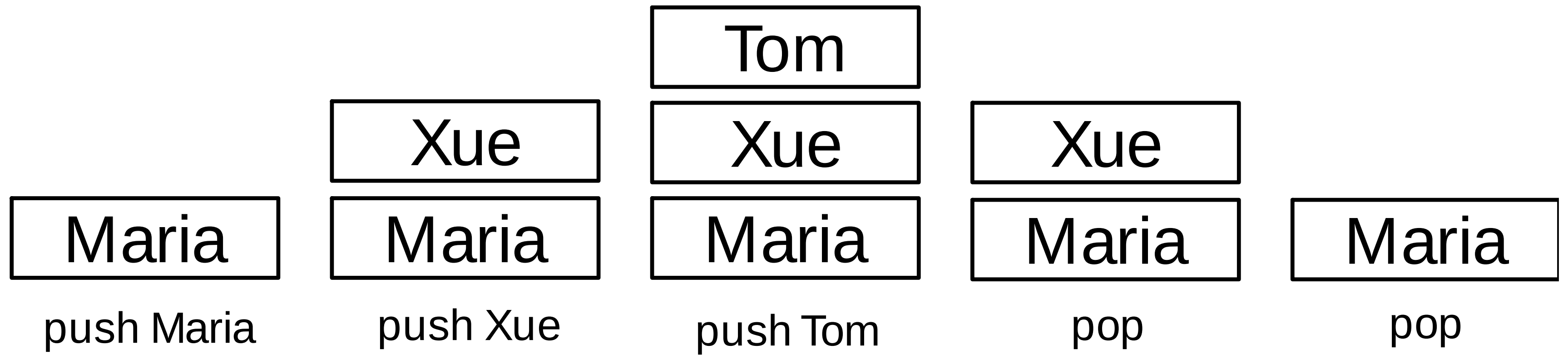
Queue: ordered list

- First In, First Out (**FIFO**); Key ops: ENQUEUE, DEQUEUE
- A list restricted to adding to the end and deleting from the front
- Most commonly an array implementation



Stacks: like stacks of plates

- Most commonly an array implementation
- First In Last Out (**FILO**); key ops: PUSH, POP
- Just a list restricted to adding items to end and taking from end
- For us, used as “work list” for non-recursive tree walking
- Also reverses a sequence; push Maria,Xue,Tom; then pops give: Tom,Xue,Maria



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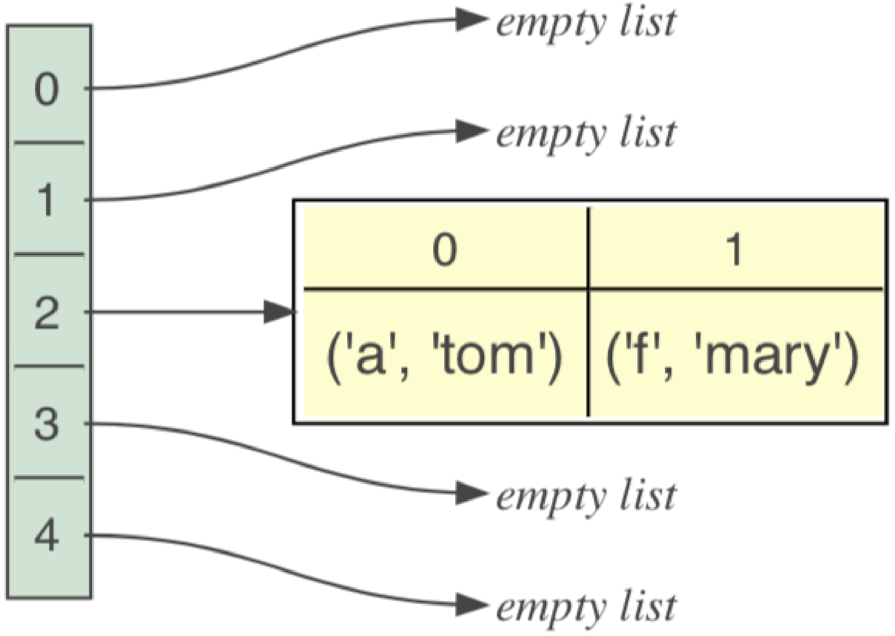
Set: unordered, unique collection

- Typical implementation is a hash table
- Operations are add, delete, contains, union, intersection, etc…
- “contains” operation takes constant time O(1) for hashtable implementation
- Hashtable impl maps key to 1, True, or similar (value is ignored)

Dictionary abstract data structure

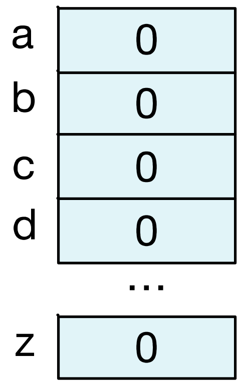
- Maps key to value; i.e., d[key] = value
- Look up values by key; i.e., d[key]
- Hashtable is implementation of choice
- Recall hashtable is array of buckets, each bucket is array of (key,value) pairs
- Hashcode is function of key then mod with len(htable) to get bucket index; add key/value pair to that bucket



Q: *What is most efficient char counting method you can think of?*

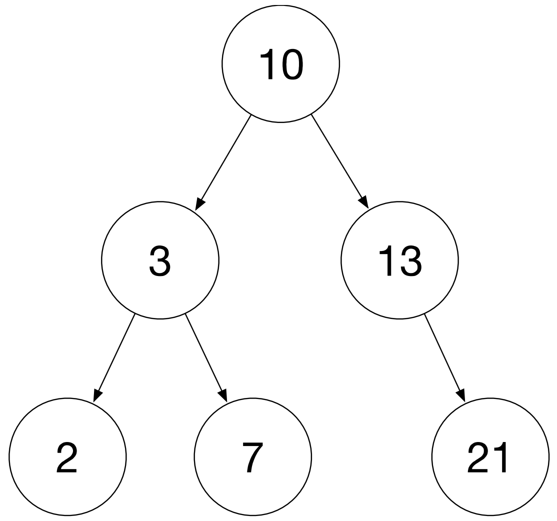
- Must update a char’s count in O(1), one unit of work
- Screams out for a dictionary
- Is hashtable best implementation?
- Chars are a..z, so identify function is a trivial, perfect hash

```
for c in s:
    count[c-ord('a')] += 1
```

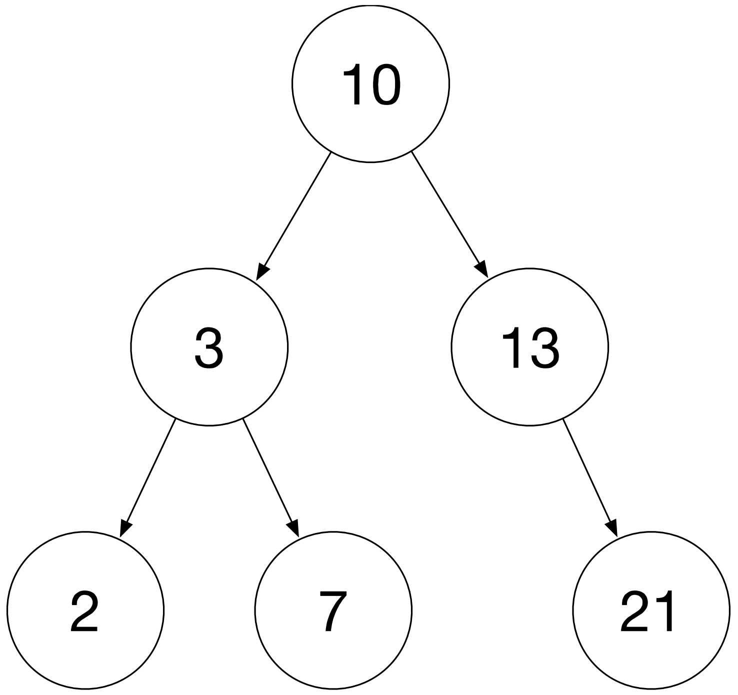


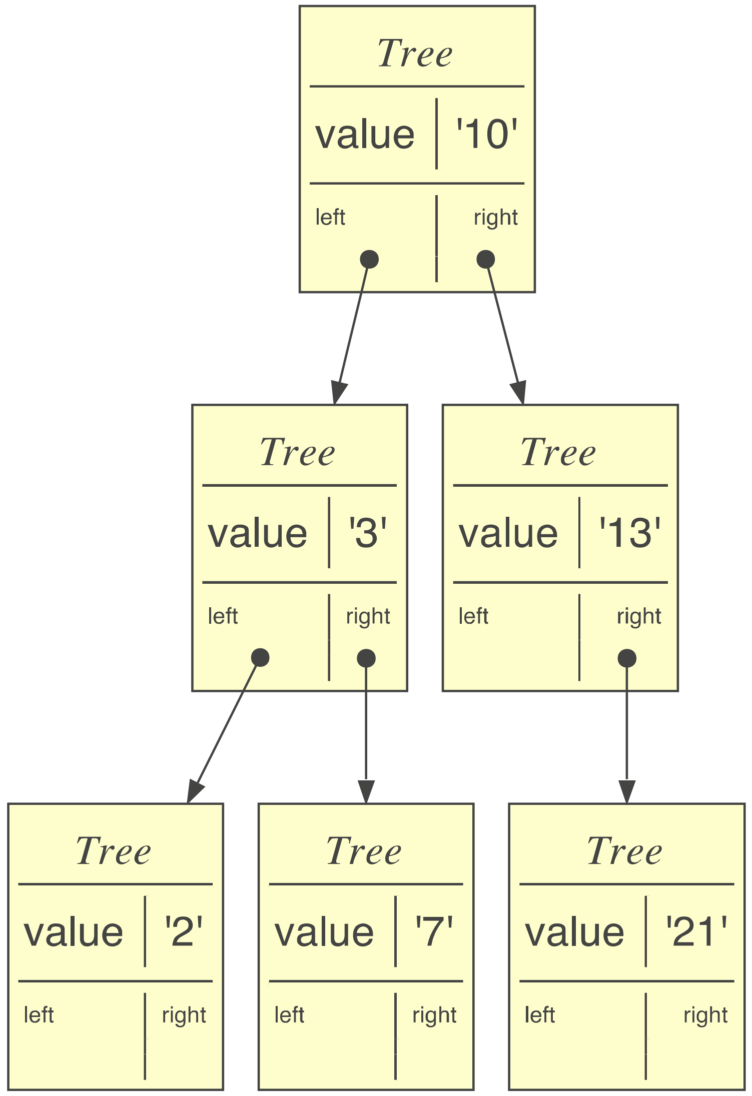
Binary tree abstract data structure

- A directed-graph with internal nodes and leaves
- No *cycles* and each node has at most one parent
- Each node has at most 2 child nodes
- For n nodes, there are n-1 edges
- A *full* binary tree: all internal nodes have 2 children
- Height of full tree with n internal nodes is about log2(n)
- Height defined as number of edges along path root->leaf
- Level 0 is root, level 1, …
- Note: binary tree doesn't imply *binary search tree*



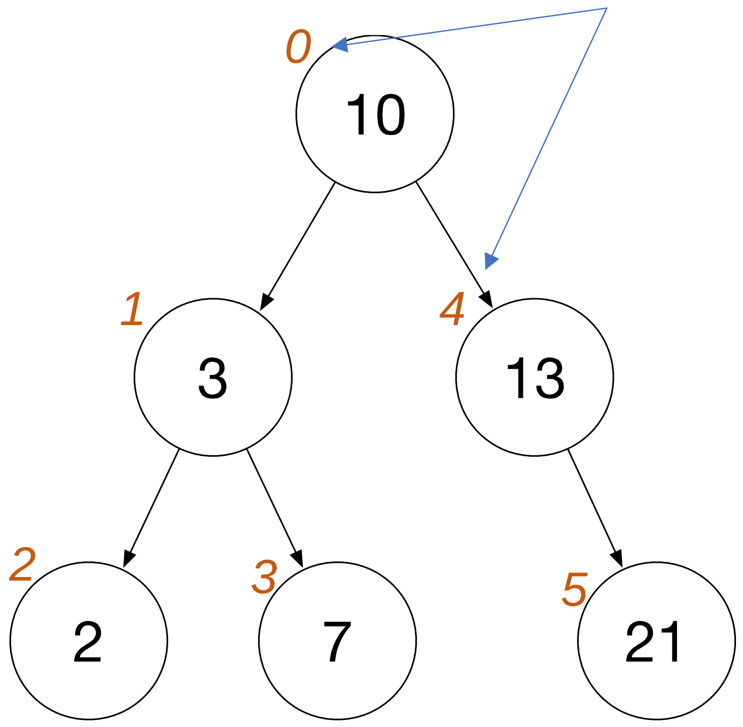
Binary tree implementation using pointers





Indexes as pointers

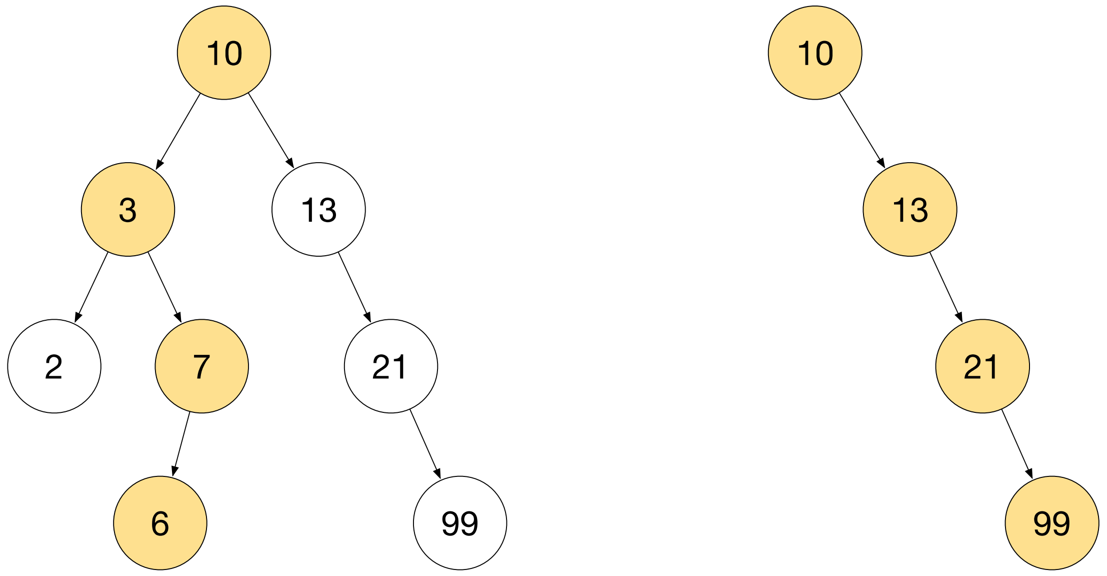
- sklearn doesn't use nodes with pointers as it requires an object for each tree node, which is expensive (objects have overhead)
- Instead, it uses node IDs and parallel arrays like *left*, *right*, *value*



left[0] = 1	right[0] = 4	value[0] = 10
left[1] = 2	right[1] = 3	value[1] = 3
left[2] = -1	right[2] = -1	value[2] = 2
left[3] = -1	right[3] = -1	value[3] = 7
left[4] = -1	right[4] = 5	value[4] = 13
left[5] = -1	right[5] = -1	value[5] = 21

Binary search trees (tree with conditions)

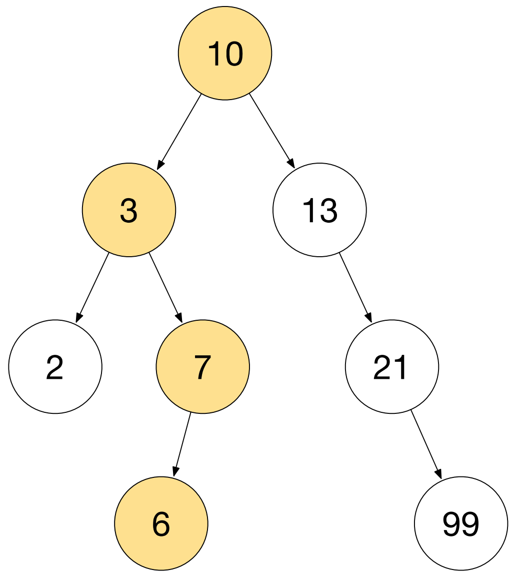
- Nodes have values
- Elements in left subtree are all less than node's value, all elements in the right subtree are greater than the node's value



Searching binary search trees

- Recursively compare search value with node value, descending into children according to relative value; e.g., search(6)

```
def search(p:TreeNode, x:object):
    if p is None: return None
    if x < p.value:
        return search(p.left, x)
    if x > p.value:
        return search(p.right, x)
    return p
```



Constructing binary search trees

- The result of the add() function is the modified tree

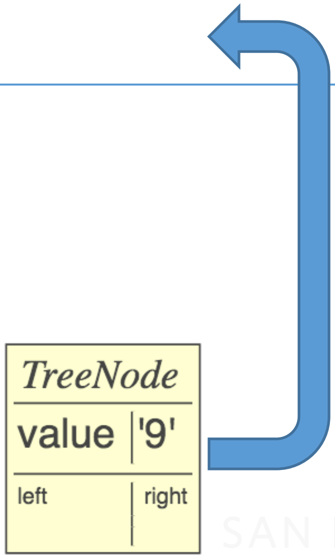
```
def add(p:TreeNode, value) -> TreeNode :
    if p is None:         return TreeNode(value)
    if value < p.value:   p.left = add(p.left, value)
    elif value > p.value: p.right = add(p.right, value)
    return p # do nothing if equal (already there)
```

- Initial condition: p is None:

```
root = add(None, 9)
```

- If node.value==value, return that node:

```
root = add(root, 9)
```

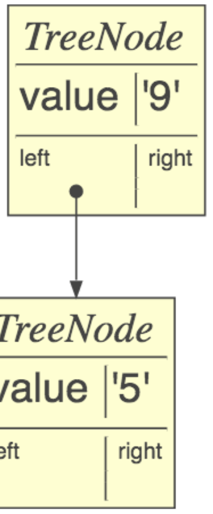


Constructing binary search trees cont'd

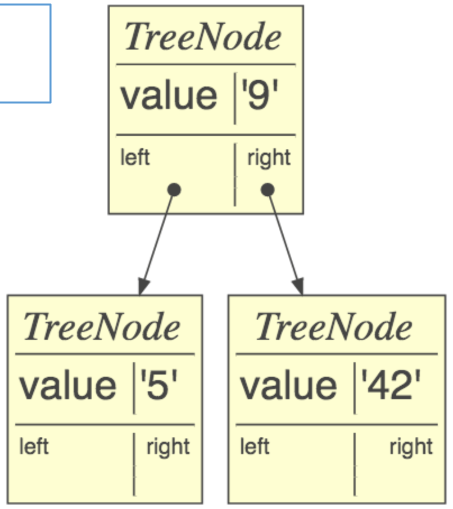
- If value < current node, add to the left, else add to right

```
if value < p.value: p.left = add(p.left, value) ...
```

```
root = add(root, 5)
```



```
root = add(root, 42)
```



Consider similarity of search / build

```
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    if p is None: return None
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        return search(p.left, x)
    if x > p.value:
        return search(p.right, x)
    return p
```
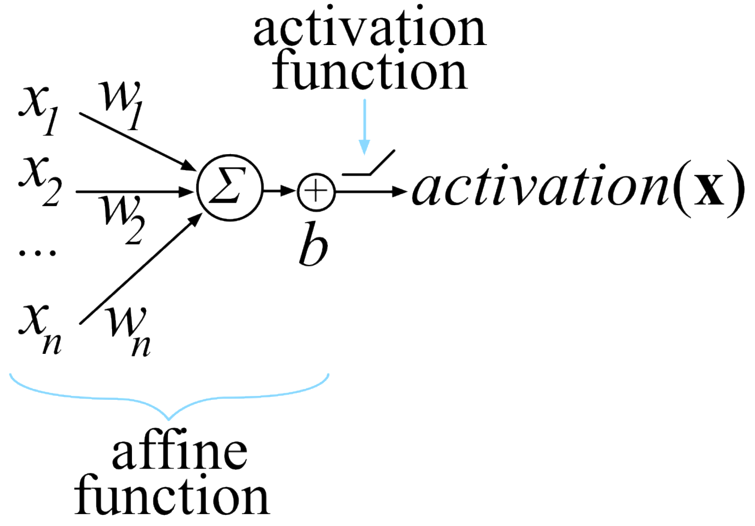
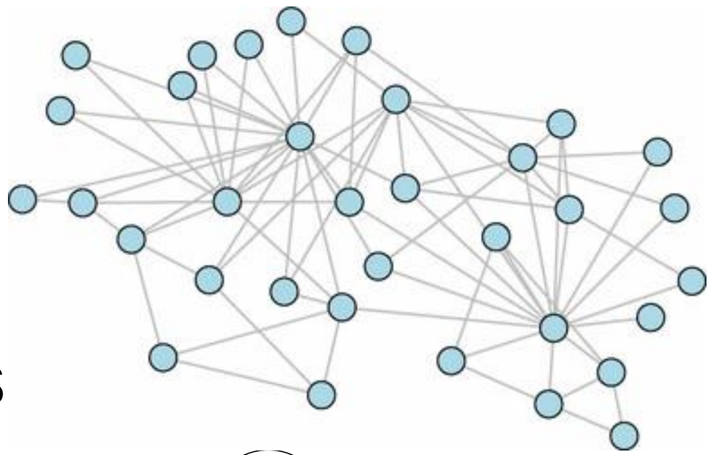
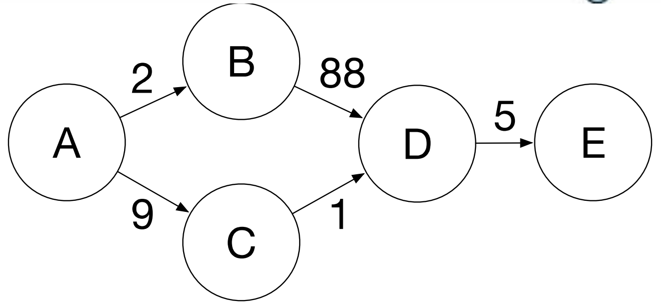

```
def add(p:TreeNode,  x:object):
    if p is None: return TreeNode(x)
    if x < p.value:
        p.left = add(p.left, x)
    elif x > p.value:
        p.right = add(p.right, x)
    return p
```

Graphs

- An arbitrary number of outgoing edges, (pointers) not just 2 like binary trees
- Can also implement with adjacency matrix
- Edges can be labeled or unlabeled
- Edges can be directed or undirected
- Nodes can be pointed at by any num of nodes
- Cycles are ok unless otherwise specified; e.g., directed acyclic graph (DAG) is a semi-common term







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Blue image from https://skymind.ai/wiki/graph-analysis

Basic node definitions

```
class LLNode:
  def __init__(self, value, next=None):
      self.value = value
      self.next = next
```

1

```
class TreeNode:
  def __init__(self, value, left=None, right=None):
    self.value = value
    self.left = left
    self.right = right
```

2

```
class Node:
  def __init__(self, value):
    self.value = value
    self.edges = [] # outgoing edges
```

n

only edges differ

Summary

- Abstract data types:
  List, Set, Queue, Stack, Dictionary, Binary tree, Graph
- Concrete implementations:
  arrays, hashtables, linked lists, node object with 1+ outgoing edge pointers
- *The questions you must ask of the data dictates the data structure and algorithms you need*
- Waste processor, memory power before brainpower
  (start with simplest data structure that will work)