CSE 331
Software Design & Implementation

Spring 2022

Section 5 – Graphs, Equals and Hashcode

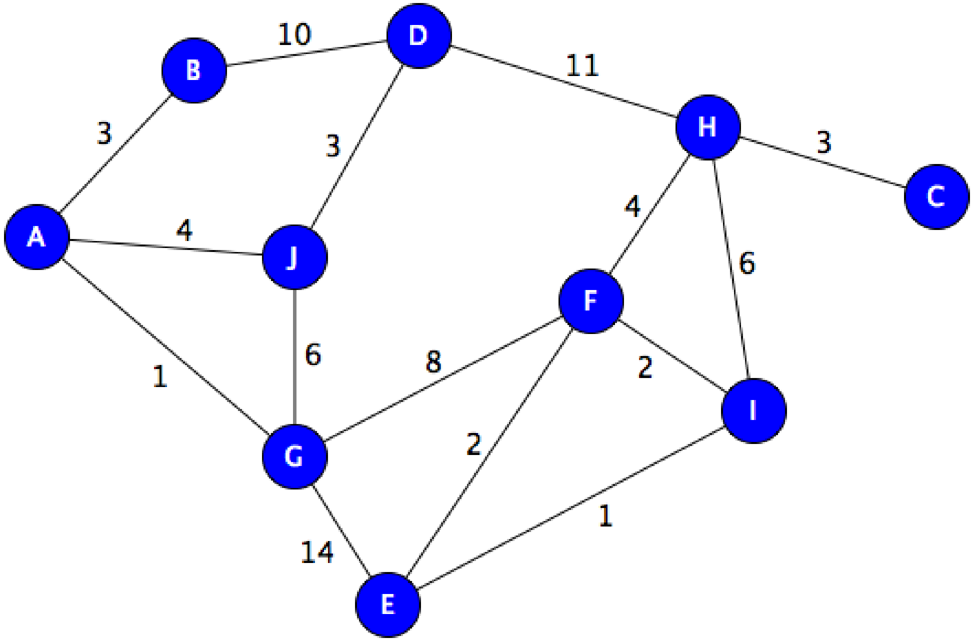
Administrivia

- HW4 due yesterday!
- HW5 out now, due next Wednesday (5/4) at 11 pm!
- Any questions?

Agenda

- Graph concepts
- HW5
- Script Testing
- Equals and Hashcode
- Extra Reasoning Practice

Graphs



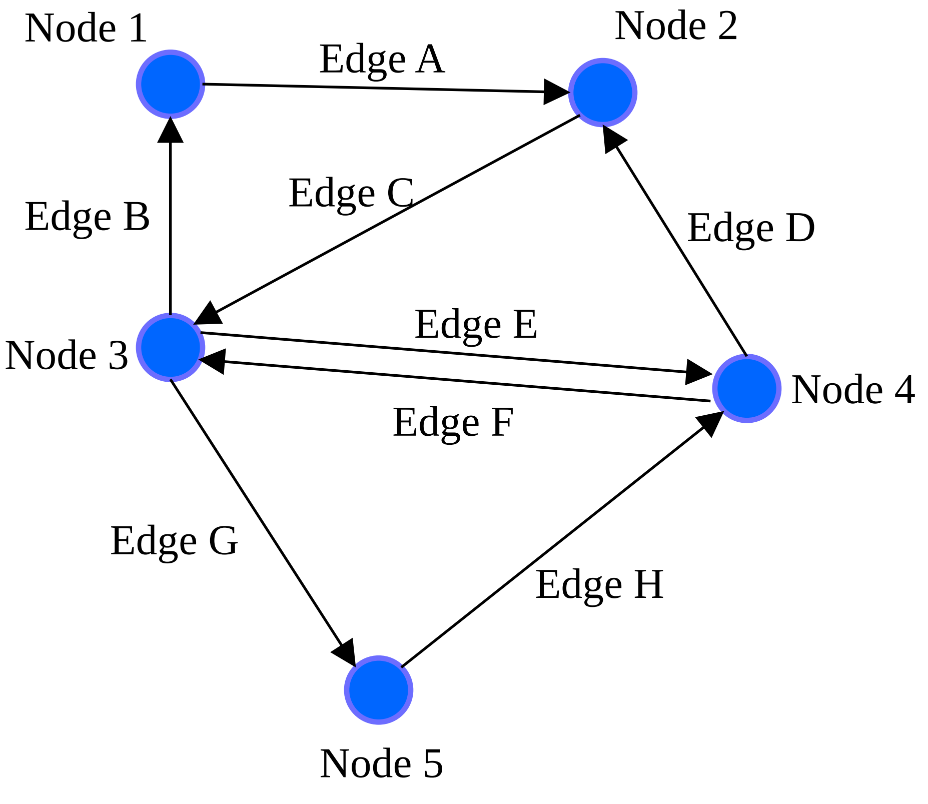
A graph represents relationships

A graph is a set of **nodes** and a set of **edges** between them.

Nodes may be **labeled**.

Edges may be **labeled**.

Edges may have a **direction**.



Example: Road Map

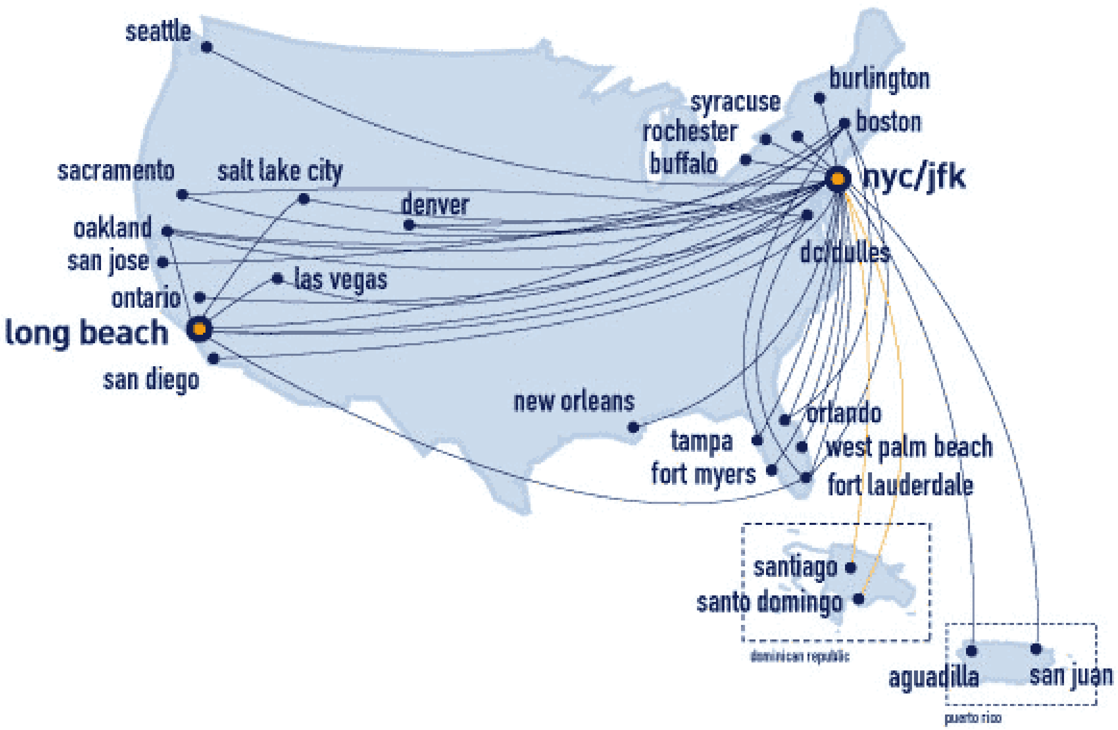
Nodes: intersections (cities)

Label: name/location

Edges: roads

Label: name/length

Example: Airline Flights



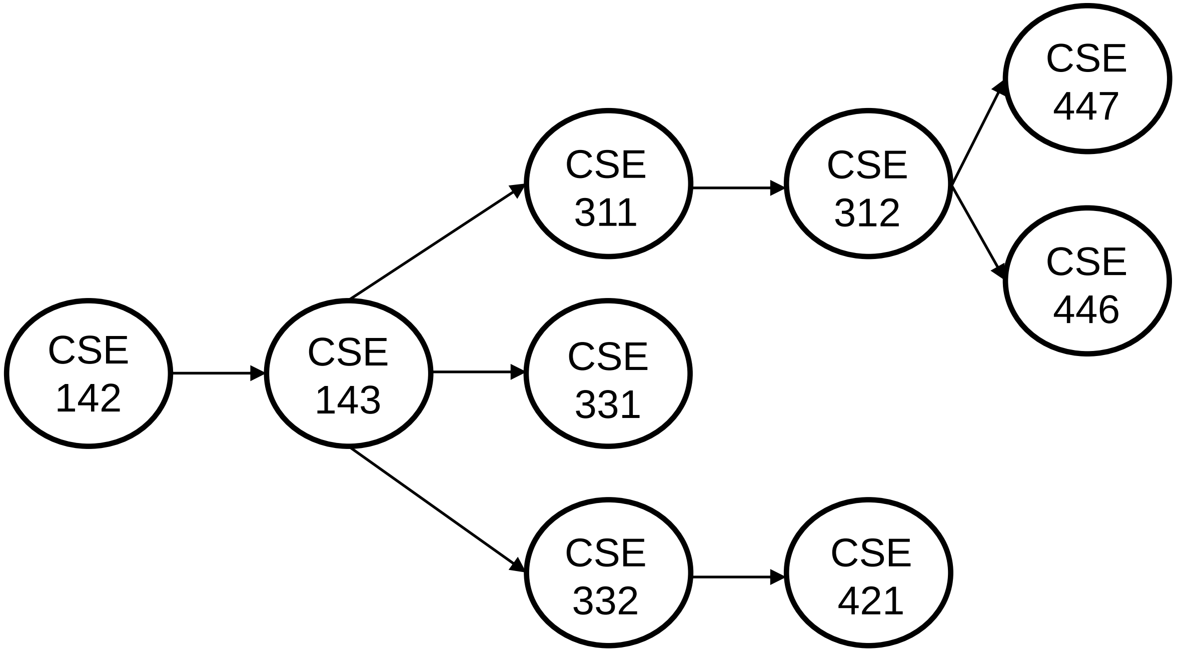
Nodes: airports

Label: airport code

Edges: flights

Label: cost/time

Example: CSE courses

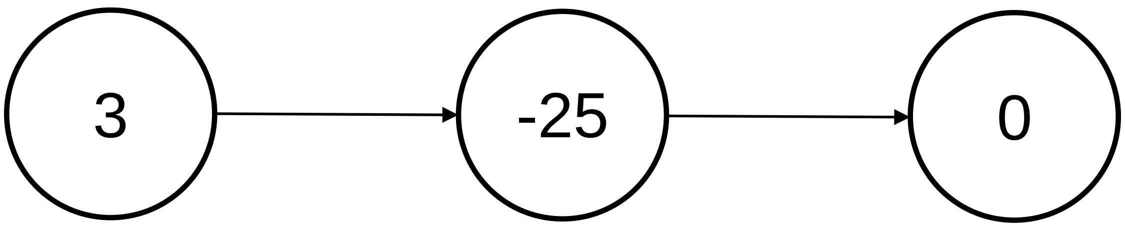


Nodes: Courses
Label: Course name

Edges: pointer to next class
Label: none

You've used graphs before!

Singly linked Lists:



Nodes: Linked list node

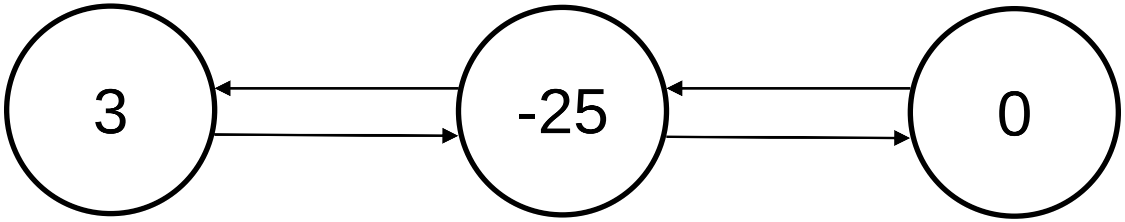
Label: integer

Edges: pointer to next node

Label: none

You’ve used graphs before!

Doubly linked Lists:



Nodes: Linked list node

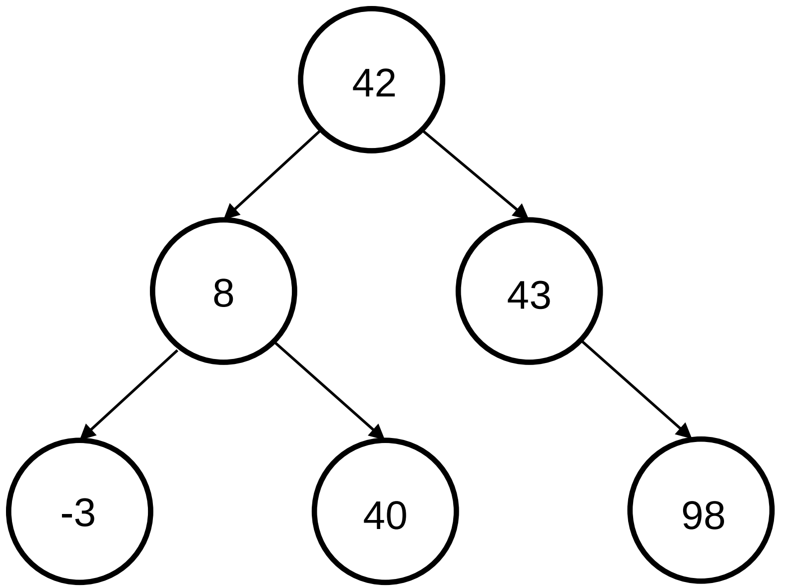
Label: integer

Edges: pointers to prev/next nodes

Label: none

You've used graphs before!

Binary trees:



Nodes: Tree node

Label: Integer

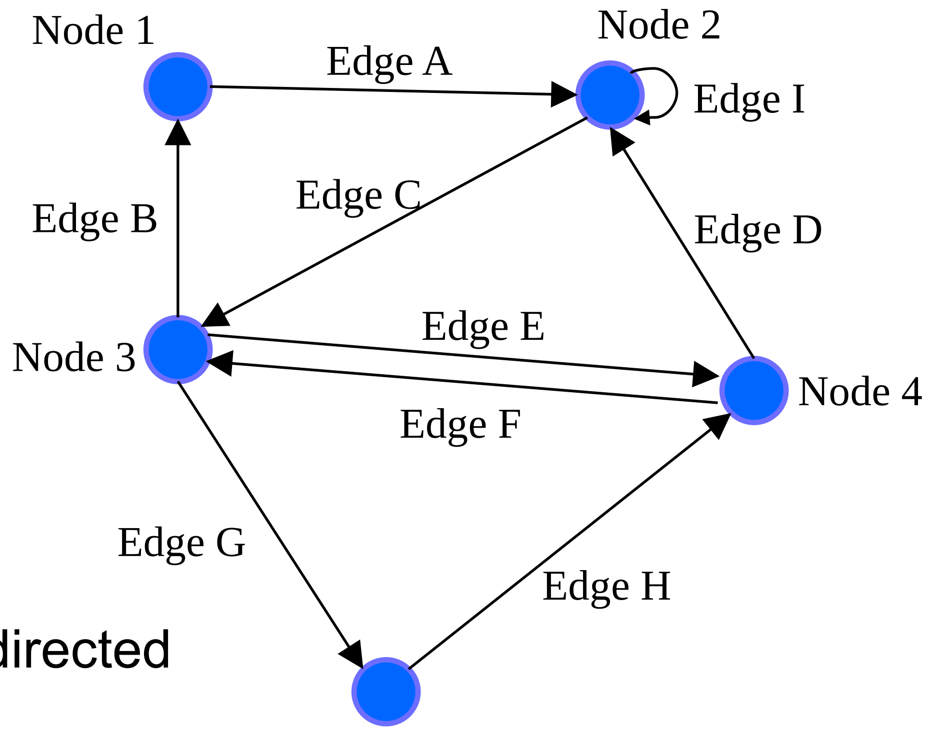
Edges: pointers to children

Label: none

An edge points from source to dest.

Each edge “points” from a source to a destination.

- **Outgoing** from source
- **Incoming** to destination

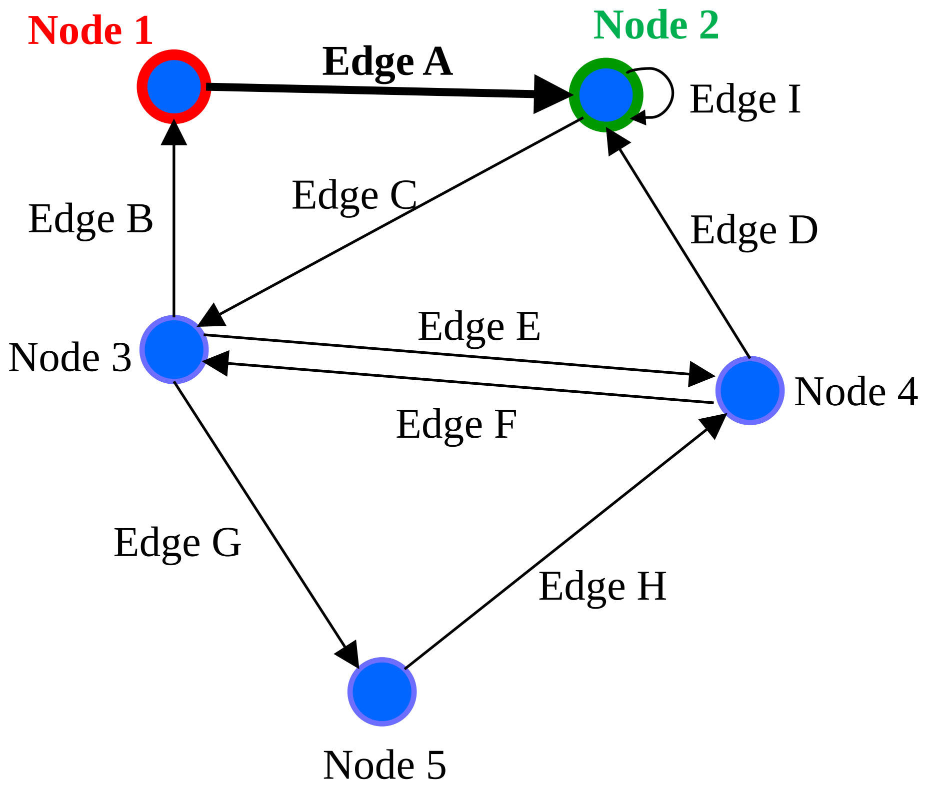


N.B.: We’re only dealing with directed graphs from here on out.

An edge points from source to dest.

Each edge “points” from a source to a destination.

- **Outgoing** from source
- **Incoming** to destination



Edge A is Node 1 → Node 2.

- Outgoing from Node 1
- Incoming to Node 2

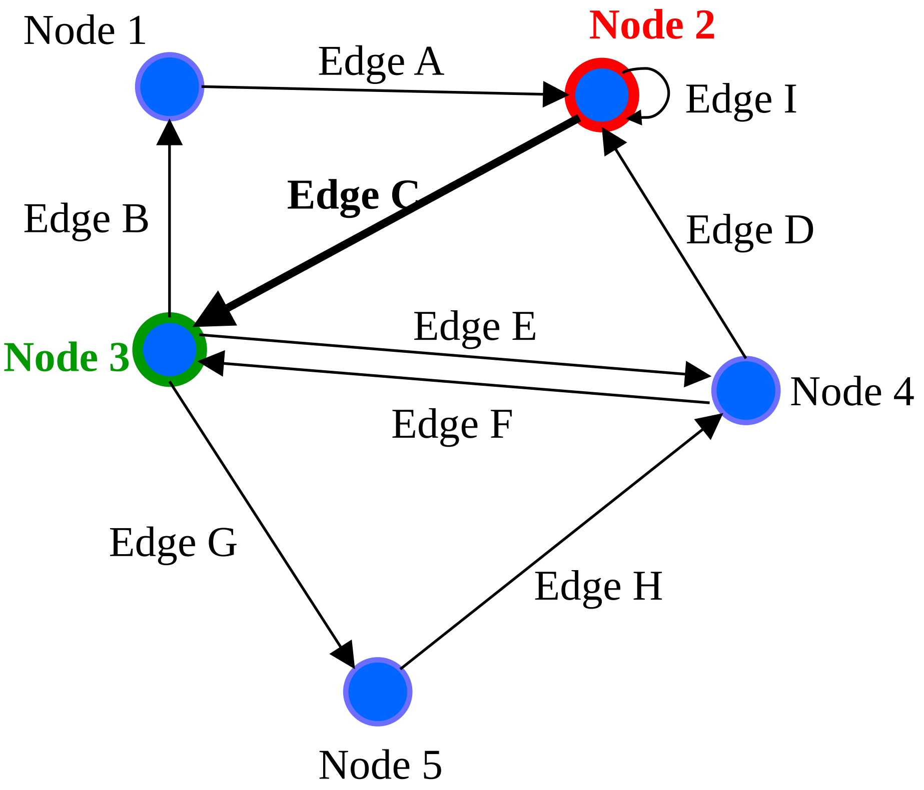
An edge points from source to dest.

Each edge "points" from a source to a destination.

- **Outgoing** from source
- **Incoming** to destination

Edge C is Node 2 → Node 3.

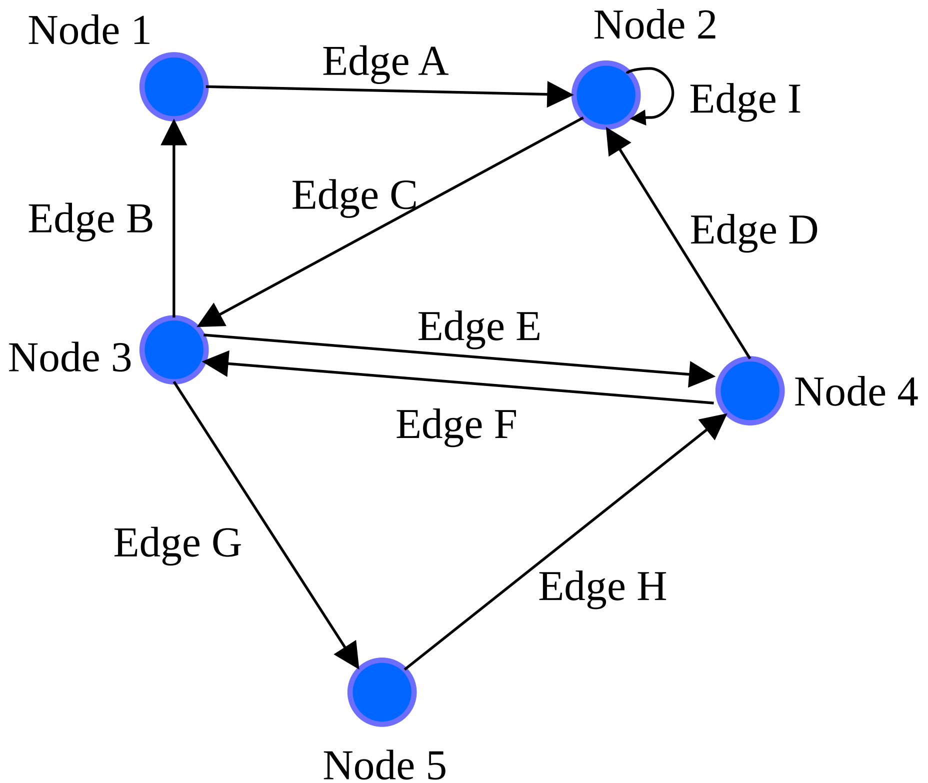
- Outgoing from Node 2
- Incoming to Node 3



A node has children

A node's outgoing edges point to its **children**.

- Potentially empty set



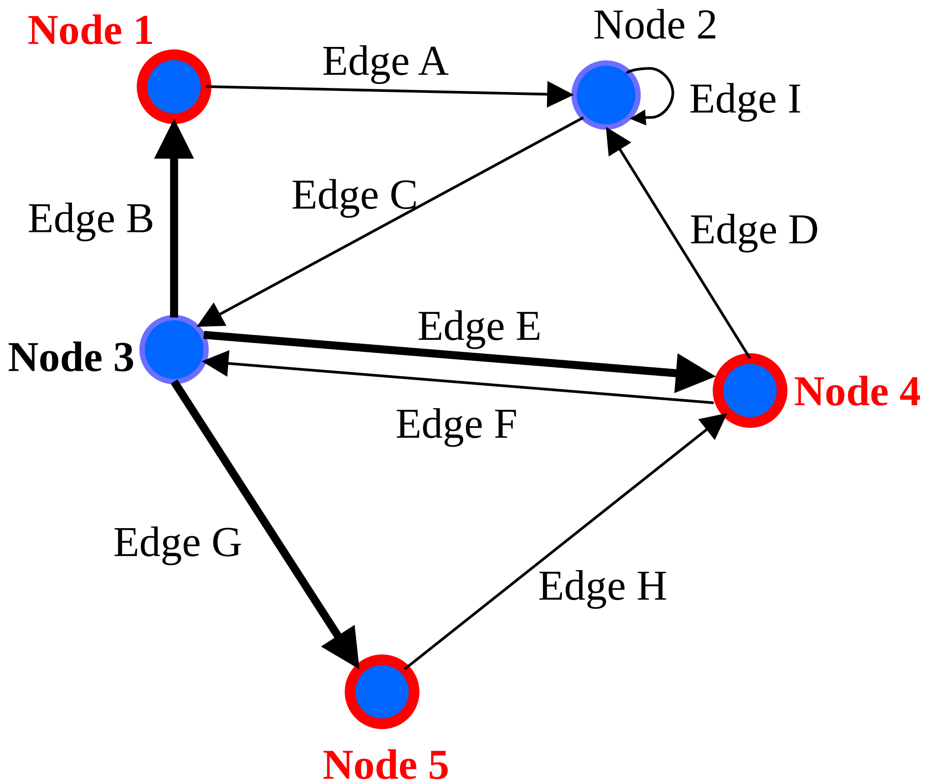
A node has children

A node's outgoing edges point to its **children**.

- Potentially empty set

Node 3 has three children:

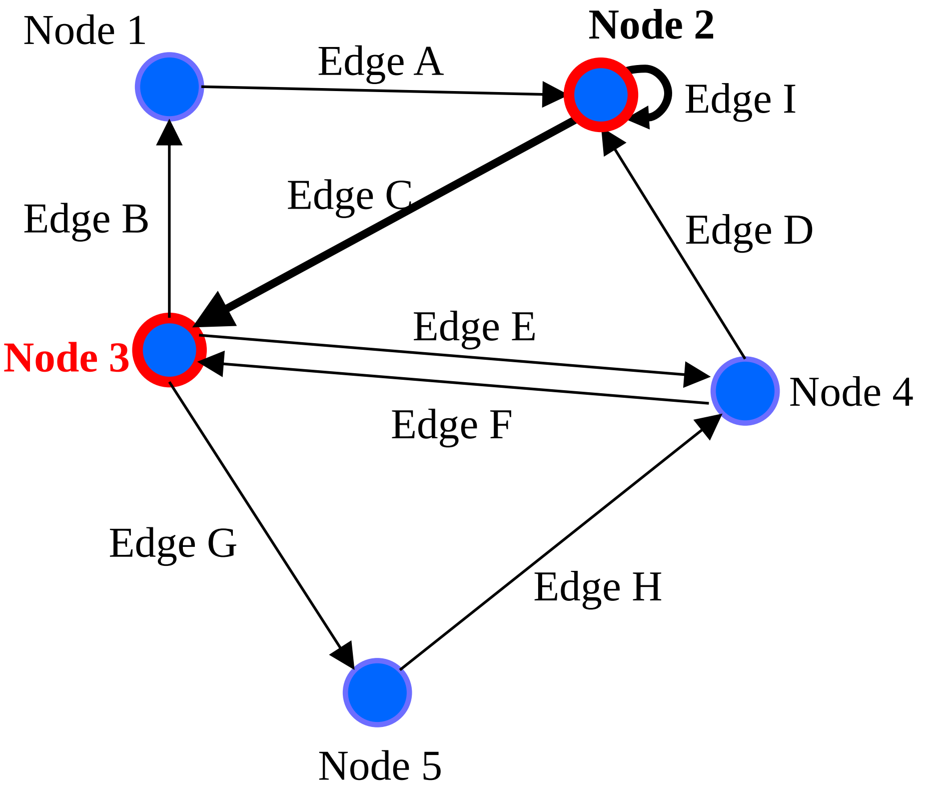
- Node 1
- Node 4
- Node 5



A node has children

A node's outgoing edges point to its **children**.

- Potentially empty set



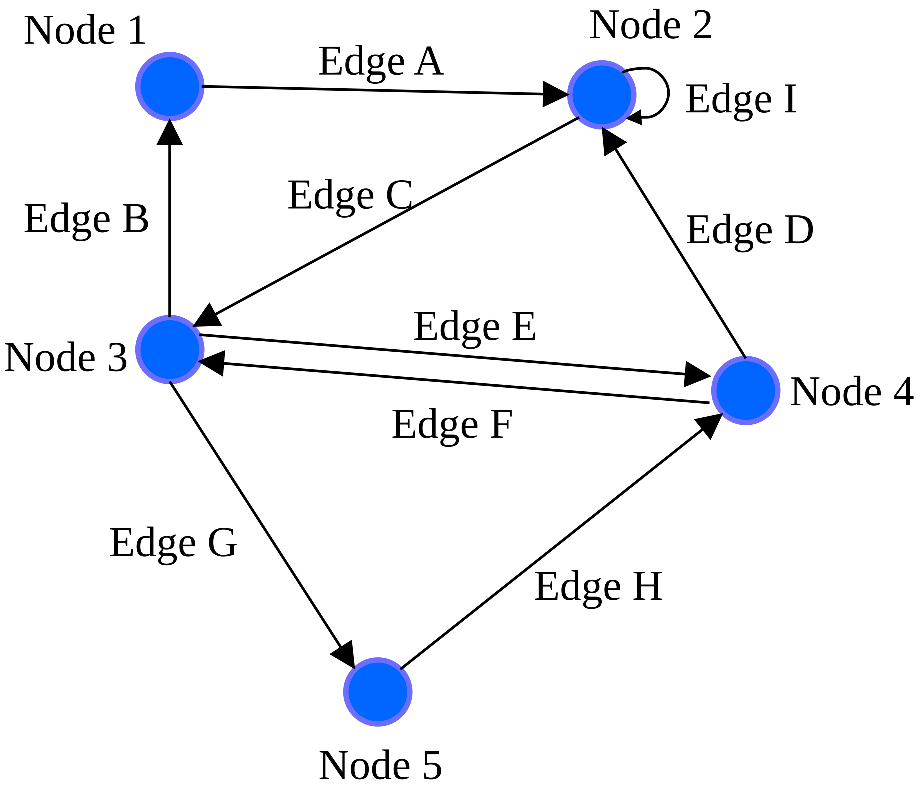
Node 2 has two children:

- Node 2
- Node 3

A node has parents

A node's incoming edges point from its **parents**.

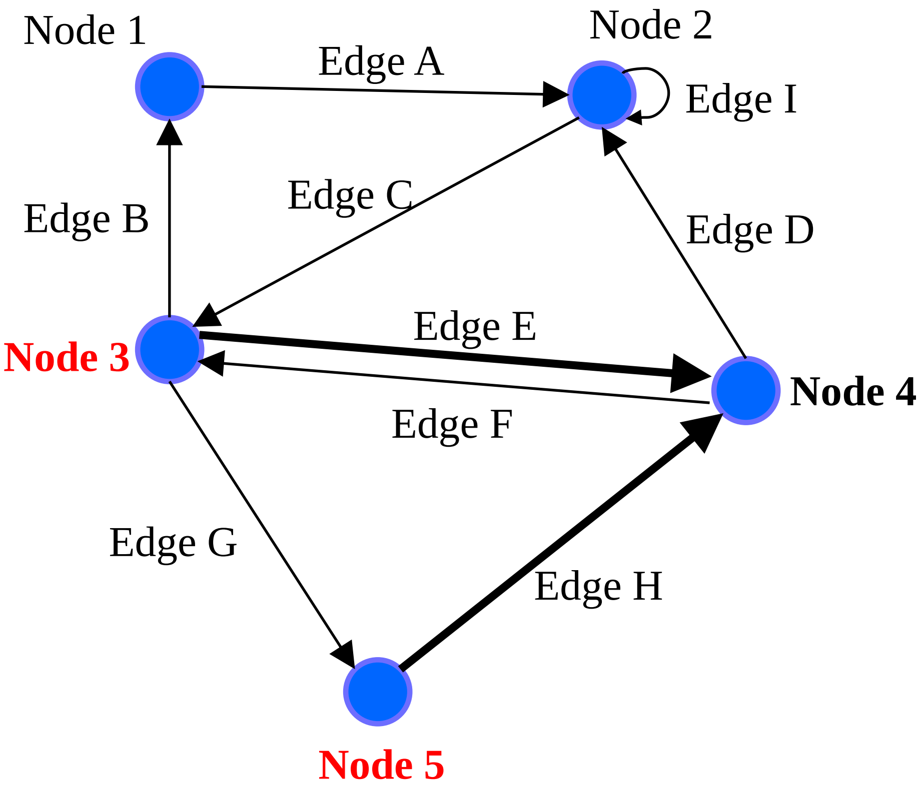
- Potentially empty set



A node has parents

A node's incoming edges point from its **parents**.

- Potentially empty set



Node 4 has two parents:

- Node 3
- Node 5

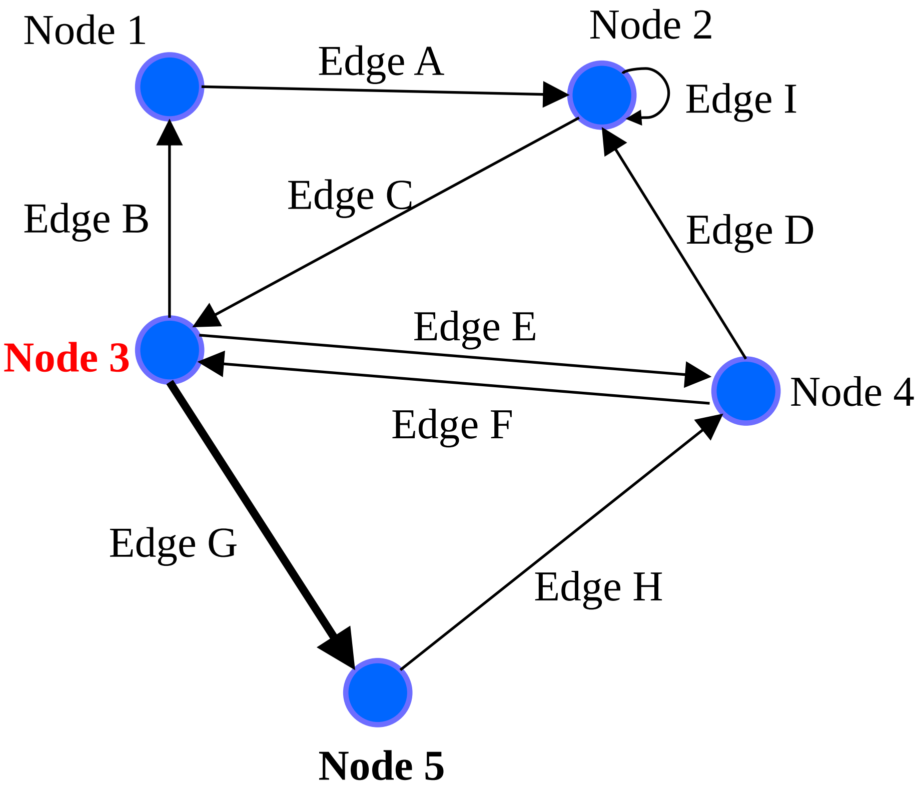
A node has parents

A node's incoming edges point from its **parents**.

- Potentially empty set

Node 5 has one parent:

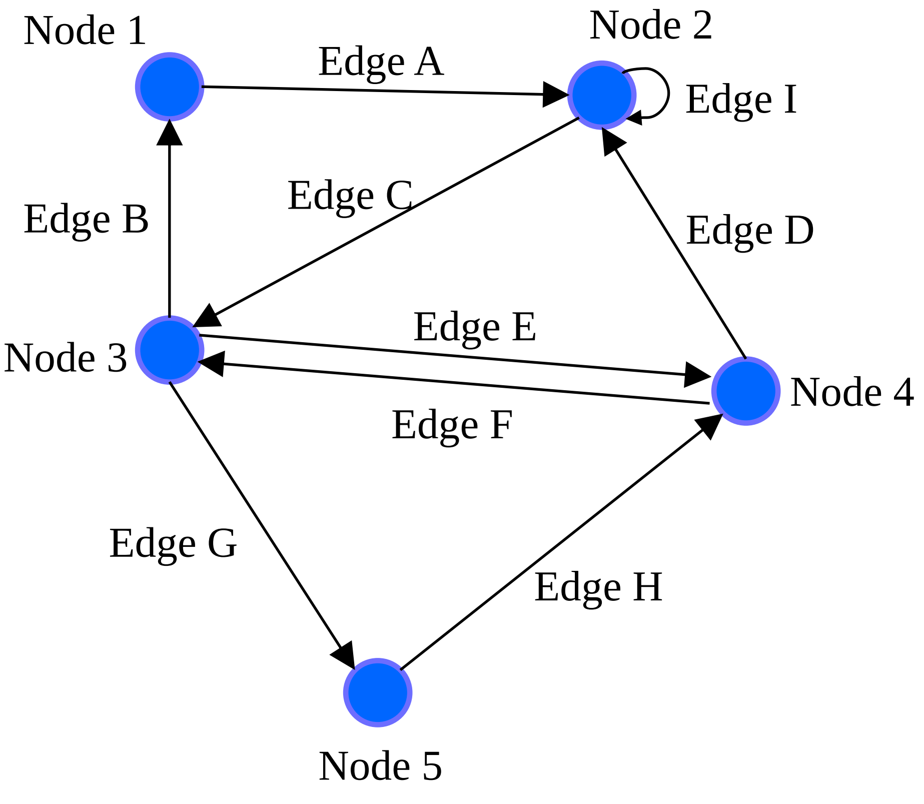
- Node 3



A node has neighbors

A node's **neighbors** are its children plus its parents.

- Potentially empty set



A node has neighbors

A node's **neighbors** are its children plus its parents.

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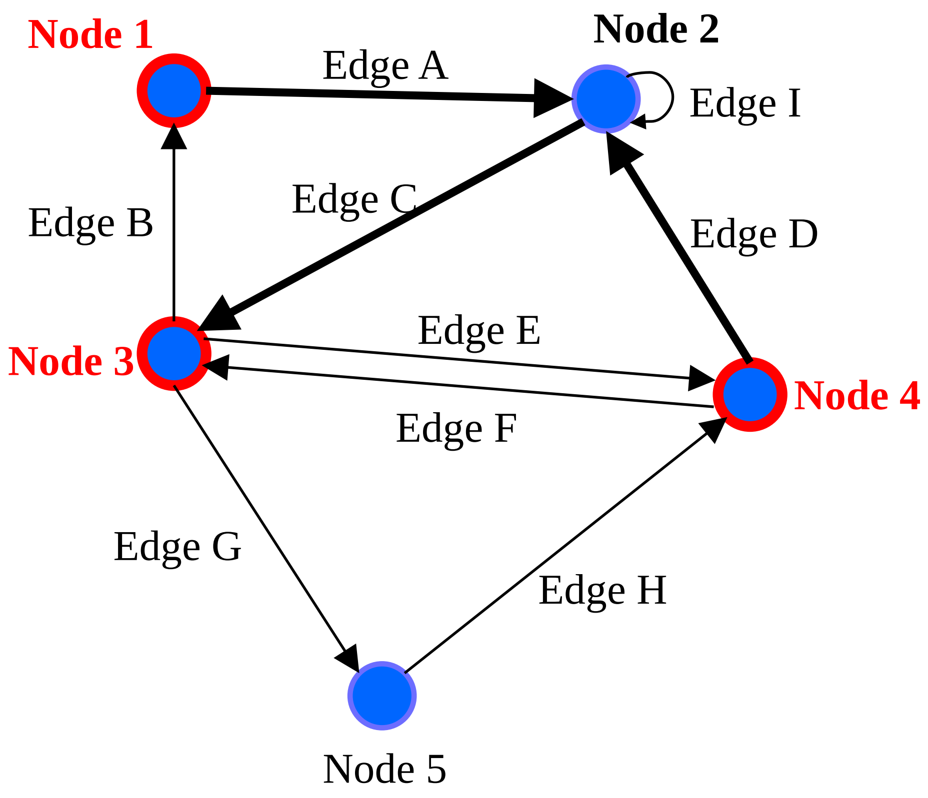


Node 2 has four neighbors:

- Node 1 (parent)
- Node 2 (self-pointing)
- Node 3 (child)
- Node 4 (parent)

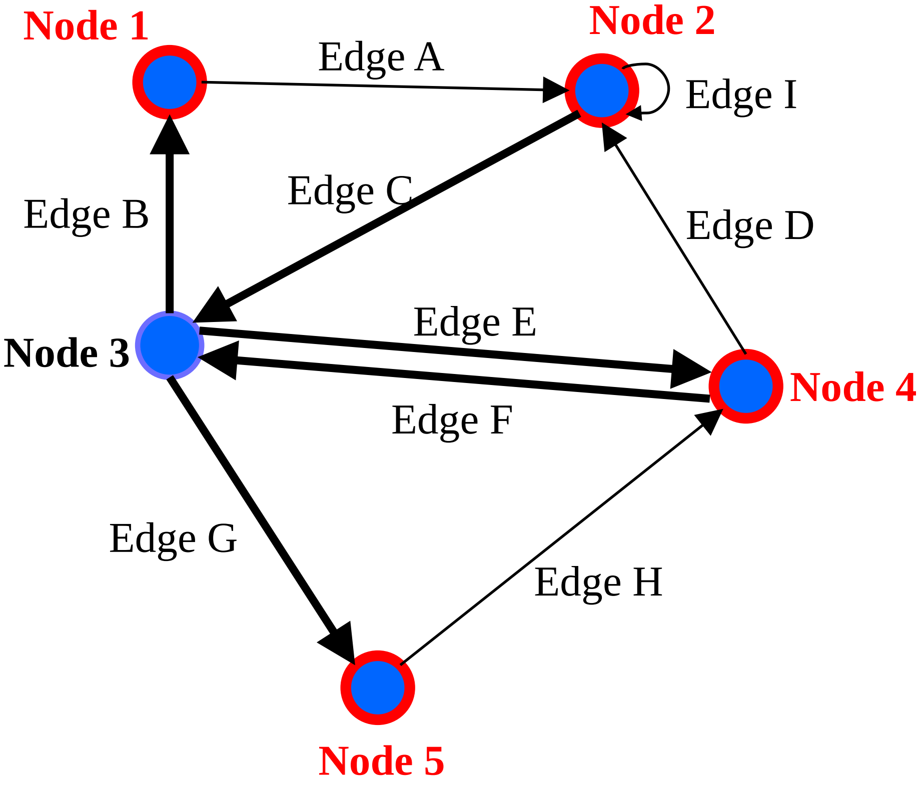
A node has neighbors

A node's **neighbors** are its children plus its parents.

- Potentially empty set

Node 3 has four neighbors:

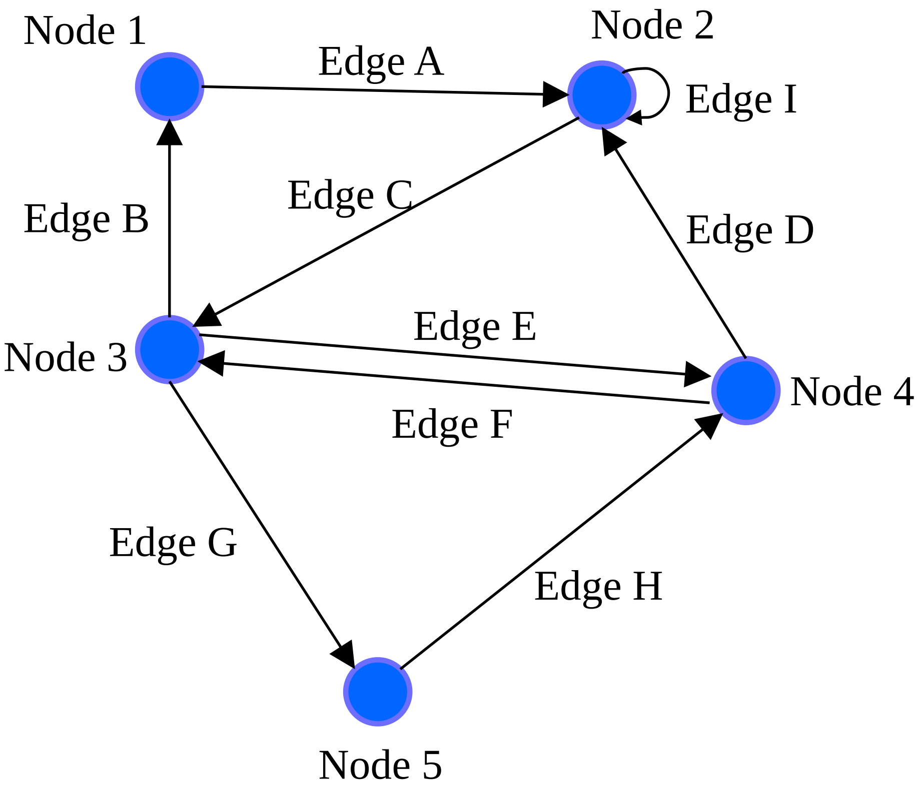
- Node 1 (child)
- Node 2 (parent)
- Node 4 (parent *and* child)
- Node 5 (child)



Paths between nodes

A **path** is a “chain” of edges from a source to a destination.

- Potentially empty sequence
- Might include a cycle
- Often want shortest



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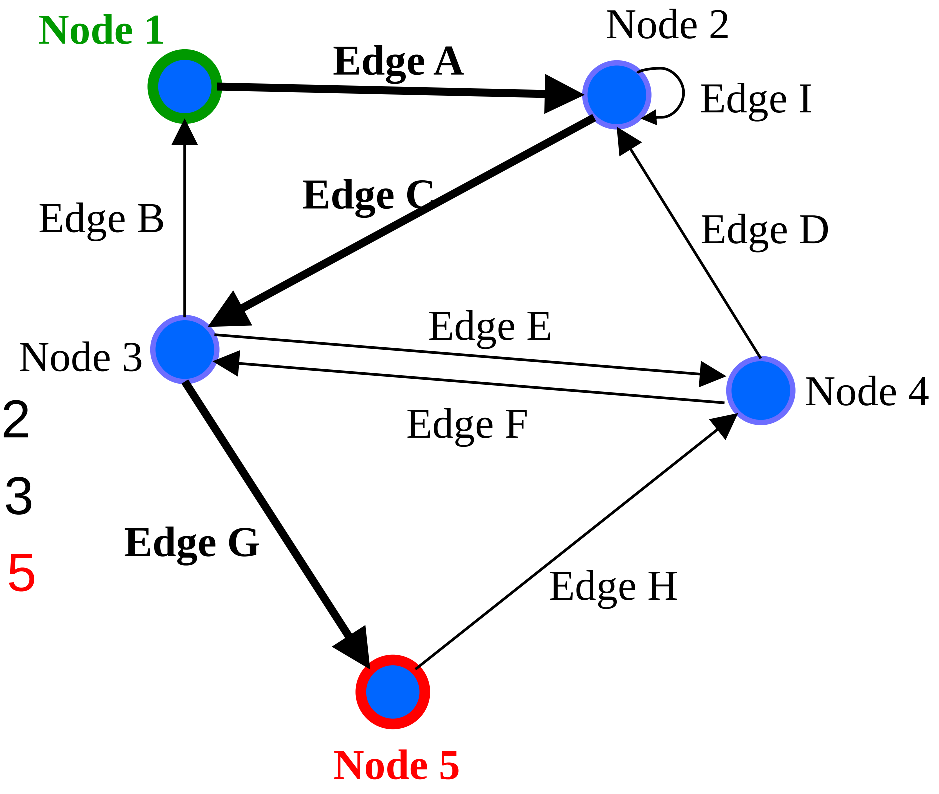


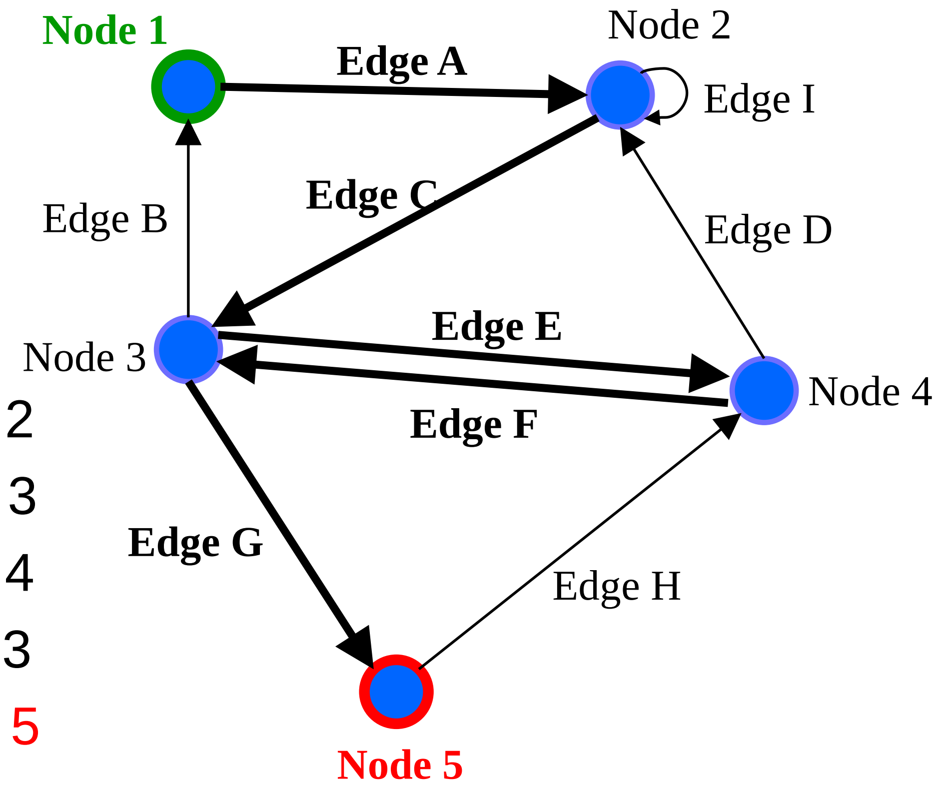
Path from Node 1 to Node 5:

1. Edge A : Node 1 → Node 2
2. Edge C : Node 2 → Node 3
3. Edge G : Node 3 → Node 5

Paths between nodes

A **path** is a "chain" of edges from a source to a destination.

- Potentially empty sequence
- Might include a cycle
- Often want shortest



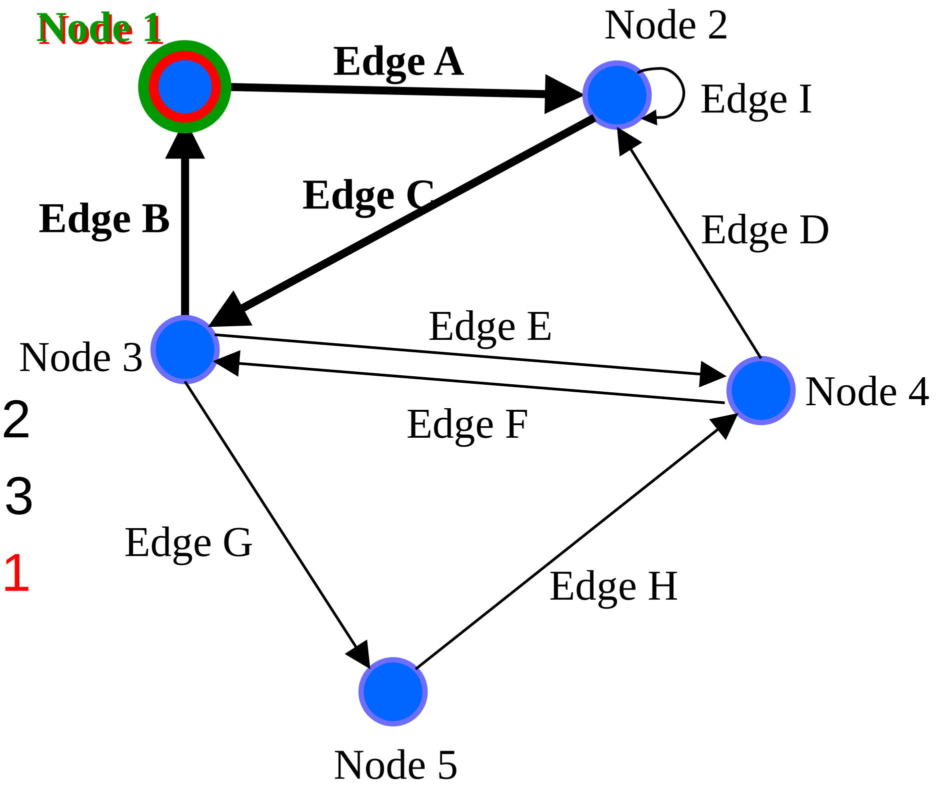
Path from Node 1 to Node 5:

1. Edge A : Node 1 → Node 2
2. Edge C : Node 2 → Node 3
3. Edge E : Node 3 → Node 4
4. Edge F : Node 4 → Node 3
5. Edge G : Node 3 → Node 5

Paths between nodes

A **path** is a “chain” of edges from a source to a destination.

- Potentially empty sequence
- Might include a cycle
- Often want shortest



Path from Node 1 to Node 1:

1. Edge A : Node 1 → Node 2
2. Edge C : Node 2 → Node 3
3. Edge B : Node 3 → Node 1

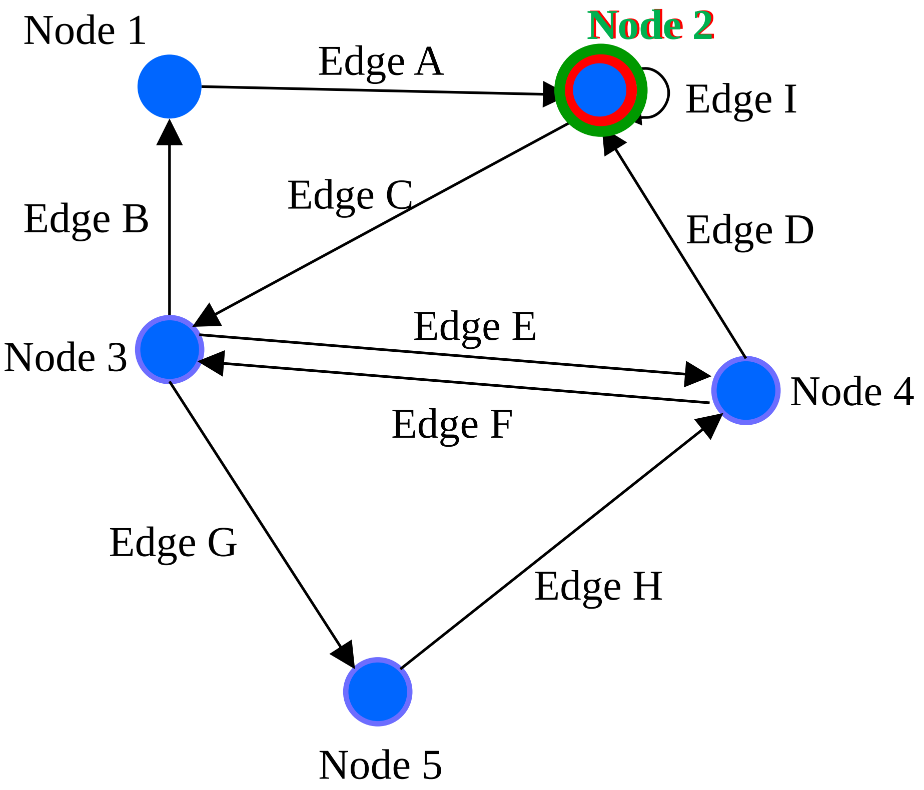
Paths between nodes

A **path** is a "chain" of edges from a source to a destination.

- Potentially empty sequence
- Might include a cycle
- Often want shortest

Path from Node 2 to Node 2:

1. Edge I : Node 2 → Node 2



Possible graph operations

Creators

- Construct an empty graph

You *might or might not* want to include all of these operations in your graph ADT design.

Observers

- Look up node(s) by label, children of, parents of, neighbors of, …
- Look up edge(s) by label, incoming to, outgoing from, …
- Iterate through all nodes
- Iterate through all edges

Mutators

- Insert/remove a node
- Insert/remove an edge

More observers

- Find path(s) from one node to another
- Find all reachable nodes
- Count indegree, outdegree

HW5: Design before implementation

- HW5: Building an ADT for labeled, directed graphs
  - Labeled: Nodes and edges have label values (**`String`**s)
  - Directed: Edges have direction
  - Edges with same source and destination will have unique labels
- The exact interface of your **`Graph`** class is up to you
  - So no given JUnit tests bundled with the starter code
  - Reminder: *Not a generic class.*
- HW5 is just designing and specifying the ADT
  - HW6 will be implementing it

HW5: What's Included

- Your submission for HW5 should include:
  - Java class(es) that represent your ADT
    - Each with method stubs
  - Specifications for **all** classes and methods
  - Tests for your ADT
    - JUnit and Script tests (coming soon...)

- Your submission for HW5 should **not** include:
  - Any implemented methods
  - Anything private (fields, methods, classes, etc.)
    - Including RI and AF

HW5: Specifications in JavaDoc

- Write class/method specifications in proper JavaDoc comments
  - See "Resources" → "Class and Method Specifications"

- You can generate nice HTML pages cleanly presenting all your JavaDoc specifications
  - Placed in "build/docs/javadoc/"

- This is a great way to verify the JavaDoc is formatted correctly
  - And to review/proofread your work…

- Let's look at the JavaDoc from HW4… (demo)

JavaDoc Demo

- Run the “javadoc” gradle task (in the documentation folder)

- Locate **`build/docs/javadoc/index.html`**, right-click, **Open In >** a browser of your choice
  - Look for formatting errors or missing components!

HW5: Testing

- The design process includes crafting a good test suite
  - Script tests and JUnit tests
- **Script Tests** (**`src/test/resources/testScripts/`**)
  - Test script files ***`name`*****`.test`** with corresponding ***`name`*****`.expected`**
  - Validate behavior intrinsic to high-level concept (abstract meaning)
  - Tested properties should be expected of any solution to HW5
- **JUnit Tests** (**`src/test/java/graph/junitTests/`**)
  - JUnit test classes
  - Validate behavior that can't be tested with script tests.
- If you can validate a behavior using either test type, use a script test!

HW5: Script Tests

Each script test is expressed as text-based script ***`foo.test`***

- One command per line, of the form: **`Command`** *arg*$_1$ *arg*$_2$ …
- Script's output compared against ***`foo.expected`***
- Precise details specified in the homework
- Match format ***exactly***, including whitespace!

Command (in *`foo`*`.test`)	Output (in *`foo`*`.expected`)
`CreateGraph` *name*	**`created graph`** *name*
`AddNode` *graph label*	**`added node`** *label* **`to`** *graph*
`AddEdge` *graph parent child label*	**`added edge`** *label* **`from`** *parent* **`to`** *child* **`in`** *graph*
`ListNodes` *graph*	*graph* **`contains:`** *label*$_{node}$ …
`ListChildren` *graph parent*	**`the children of`** *parent* **`in`** *graph* **`are:`** *child* **`(`***label*$_{edge}$**`)`** …
# *This is comment text …*	**#** *This is comment text …*

HW5: `example.test`

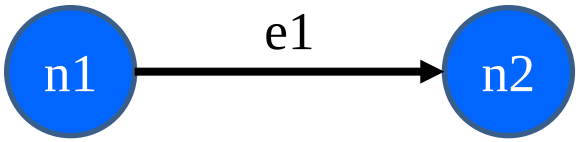
```
# Create a graph
CreateGraph graph1

# Add a pair of nodes
AddNode graph1 n1
AddNode graph1 n2

# Add an edge
AddEdge graph1 n1 n2 e1

# Print all nodes in the graph
ListNodes graph1

# Print all child nodes of n1 with outgoing edge
ListChildren graph1 n1
```



HW5: `example.expected`

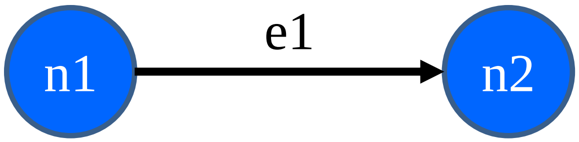
```
# Create a graph
created graph graph1

# Add a pair of nodes
added node n1 to graph1
added node n2 to graph1

# Add an edge
added edge e1 from n1 to n2 in graph1

# Print all nodes in the graph
graph1 contains: n1 n2

# Print all child nodes of n1 with outgoing edge
the children of n1 in graph1 are: n2(e1)
```



HW5: Why Script Tests?

- Everyone's implementation could (will!) be different, so we (staff) cannot write JUnit tests for everyone to use or to use for checking everyone's code.

- We still need a way to test that you specify and implement the proper behavior, so we use script tests that work regardless of the implementation.

- They test what the methods are doing, they don't care how the methods are doing it.

HW5: Creating a script test

1. Write test steps as script commands in a file ***`foo`*****`.test`**
2. Write expected ("correct") output in a file ***`foo`*****`.expected`**
   - …taking care to match the output format *exactly*
3. Place both files under **`src/test/resources/testScripts/`**
4. Run all such tests via the Gradle task **`scriptTests`**
   - After class implemented and **`GraphTestDriver`** stubs filled

HW5: Test Commands vs Methods

- Your graph should not have the exact same interface as the script test commands
  - e.g. you should not have a method called **AddNode()** that adds a node to the graph and prints out/returns the string "added node n1 to graph1"
  - This wouldn't make much sense for other graph clients!

- But you will need the ability to add a node!

- Later, we will need some way to map script test commands (**`AddNode graph1 n1`**) to some Java code that uses the methods of your graph class
  - This is part of HW6; do not worry about for now

HW5: Script tests vs. JUnit Tests

- Script tests will not cover every case for your graph:
  - What if you have additional methods that can’t be tested by our script test commands?
  - What about “bad” input for your graph?
  - What happens when you try to add the same node twice?
  - …

- We need some way to test cases that cannot be covered by our script tests

- For this, we use JUnit tests.

HW5: Creating JUnit tests

1. Create JUnit test class in **`src/test/java/graph/junitTests/`**
2. Write a test method for each unit test
3. Run all such tests via the Gradle task **`junitTests`**

```
import org.junit.*;
import static org.junit.Assert.*;

/** Document class... */
public class FooTests {
  /** Document method... */
  @Test
  public void testBar() { ... /* JUnit assertions */ }
}
```

HW5: Creating JUnit tests

- Note: Your JUnit tests will fail in HW5, because you have not implemented the actual methods yet
  - The same goes for your script tests
- You will get them passing in HW6

Equals and Hashcode

The `equals` method (review)

- Specification mandates several properties:
  - *Reflexive*: **`x.equals(x)`** is **`true`**
  - *Symmetric*: **`x.equals(y)`** $\Leftrightarrow$ **`y.equals(x)`**
  - *Transitive*: **`x.equals(y)`** $\wedge$ **`y.equals(z)`** $\Rightarrow$ **`x.equals(z)`**
  - *Consistent*: **`x.equals(y)`** shouldn't change, unless perhaps **`x`** or **`y`** did
  - *Null uniqueness*: **`x.equals(null)`** is **`false`**

- Several notions of equality:
  - *Referential*: literally the same object in memory
  - *Behavioral*: no sequence of operations could tell apart (excluding **==**)
  - *Observational*: no sequence of observer operations could tell apart (excluding **==**)

The `hashCode` method (review)

- Specification mandates several properties:
  - *Self-consistent*: **`x.hashCode()`** shouldn't change, unless **`x`** did
  - *Equality-consistent*: **`x.equals(y)`** ⇒ **`x.hashCode() == y.hashCode()`**

- Equal objects *must* have the same hash code.
  - Implementations of **`equals`** and **`hashCode`** work together for this
  - If you override **`equals`**, you ***must*** override **`hashCode`** as well

- Ideally a good **`hashCode`** method returns different values for unequal objects, but the contract does not require this.

Overriding **`equals`** and **`hashCode`**

- A subclass method overrides a superclass method, when…
  - They have the exact same name
  - They have the exact same argument types
- An overriding method should satisfy the overridden method's spec.
- Always use **`@override`** tag when overriding **`equals`** and **`hashCode`** (or any other overridden method)
- Note: Method overloading is not the same as overriding
  - Same name but distinguished by different argument types
- Keep these details in mind if you override **`equals`** and **`hashCode`**.

`equals` and **`hashCode`** worksheet

- Let's practice…

More Reasoning Practice

`intToString()`

Fill in the implementation of a method that converts a **positive integer** to its **string representation in decimal** (invariant given on next slide).

```
{{ P: x > 0 }}
String intToString(int x)
```

Useful facts to recall:

1. Convert **`char ch`** that is one of **`'0','1',…,'9'`** to a corresponding int by doing **`ch – '0'`**
2. Convert **`int x`** that is one of **`0,1,…,9`** to a corresponding char by doing **`(char) (x + '0')`**

`intToString()`

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf =
  int k =  , y =  ;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {



   k = k + 1;
  }

  return buf.reverse().toString();
}
```

How do we get the invariant to hold initially?

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {



   k = k + 1;
  }

  return buf.reverse().toString();
}
```

How do we fill out the loop body?

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {



   k = k + 1;
  }

  return buf.reverse().toString();
}
```

Inv changes k to k+1, so

- y becomes x / 10^{k+1}
- y_{post} = x / 10^{k+1} = y_{pre} / 10

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {


   y = y / 10;
   k = k + 1;
  }

  return buf.reverse().toString();
}
```

Inv changes k to k+1, so

- y becomes x / 10^{k+1}
- y_{post} = x / 10^{k+1} = y_{pre} / 10

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {


   y = y / 10;
   k = k + 1;
  }

  return buf.reverse().toString();
}
```

Inv changes k to k+1, so

- buf stores lowest k+1 digits

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {


   y = y / 10;
   k = k + 1;
  }

  return buf.reverse().toString();
}
```

Inv changes k to k+1, so

- buf stores lowest k+1 digits

(k+1)-st lowest digit goes at end since buf stores them reversed

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {
   char ch = ?
   buf.append(ch);
   y = y / 10;
   k = k + 1;
  }

  return buf.reverse().toString();
}
```

How can we get the (k+1)-st lowest digit of x? And make it a char?

intToString()

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {
   char ch = (char) (y % 10 + '0');
   buf.append(ch);
   y = y / 10;
   k = k + 1;
  }

  return buf.reverse().toString();
}
```

`intToString()` solution

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {
   char ch = (char) (y % 10 + '0');
   buf.append(ch);
   y = y / 10;
   k = k + 1;
  }
  {{ buf stores the digits of x in reverse order }}
  return buf.reverse().toString();
}
```

Why does this hold?

`intToString()` solution

```
{{ P: x > 0 }}
String intToString(int x) {
  StringBuilder buf = new StringBuilder();
  int k = 0, y = x;
  {{ Inv: P and buf stores the lowest k digits of x
          in reverse order and y = x / 10^k }}
  while (y != 0) {
   char ch = (char) (y % 10 + '0');
   buf.append(ch);
   y = y / 10;
   k = k + 1;
  }
  {{ buf stores the digits of x in reverse order }}
  return buf.reverse().toString();
}
```

Why does this hold?
$y = 0 \Rightarrow x < 10^k$ so x only has k digits