# Algorithms Lab
# Tutorial Session IV

# First Steps with the BGL

# Introduction

- boost is a free collection of portable C++ libraries
- boost graph library (BGL) is for graph algorithms:
  - shortest paths
  - flows
  - matchings
  - planar graphs
- BGL is highly customizable and extensible

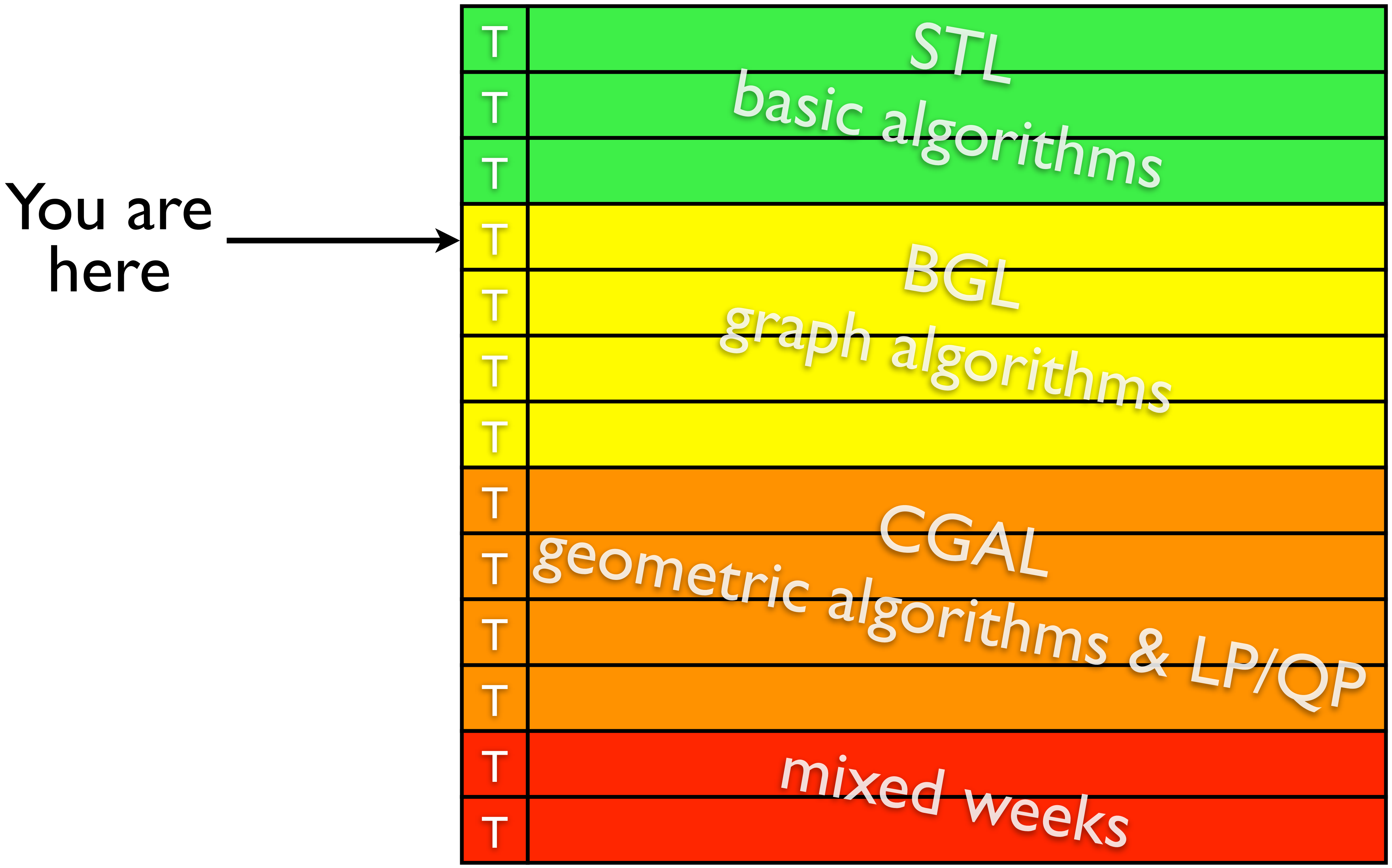
  ⇒ generic programming

# Introduction

- A short "tutorial" paper is available on moodle
  - "copy & paste tutorial"
- This presentation will also be available
- You will still need the BGL documentation a lot!
- Programming BGL requires some practice, be sure to start early!

# Introduction

## Timeline



# Introduction

## Timeline

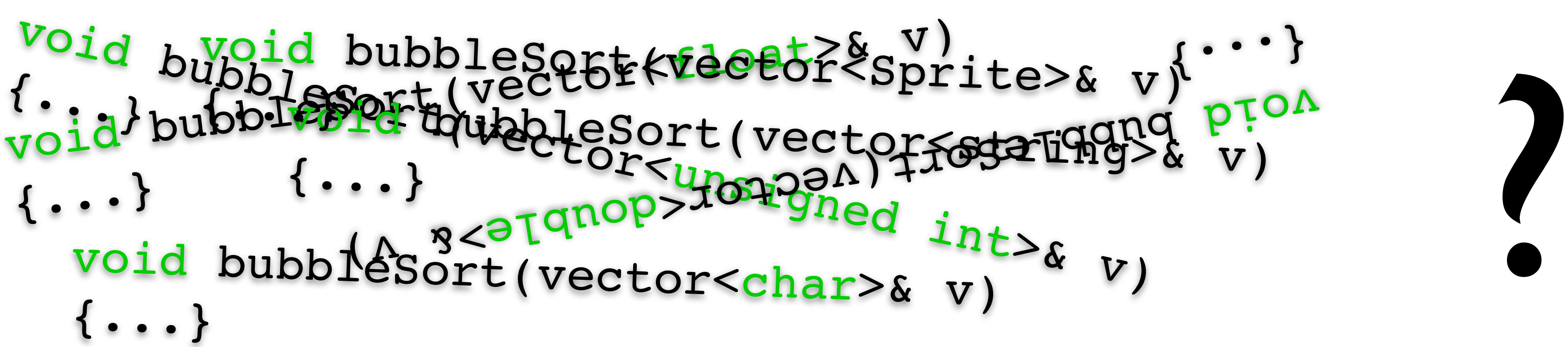
| | |
|---|---|
| T | Week I: First steps with BGL |
| T | Week II: Flow-Week |
| T | Week III: Relax-Week (Matchings) |
| T | Week IV: Surprise-Week |

# Generic Programming

# Generic Programming

```cpp
void bubbleSort(vector<int>& v)
{
  for(int i = 0; i < v.size(); ++i)
    for(int j = 0; j < v.size()-1; ++j)
      if(v[j+1] < v[j])
        swap(v[j+1], v[j]);
}
```

- What if we want to sort floats, doubles, strings, etc.?



# Generic Programming

```
template<typename T>  //'<' must be defined for T
void bubbleSort(vector<T>& v)
{
  for(int i = 0; i < v.size(); ++i)
    for(int j = 0; j < v.size()-1; ++j)
      if(v[j+1] < v[j])
        swap(v[j+1], v[j]);
}
```

- Use templates to abstract from internal type
- It is a best practice to specify our requirements for T
- What if we want to sort containers other than vector for which the '[]'-operator is sensibly defined?

# Generic Programming

```
template<typename T>
void bubbleSort(T& v)
{
  for(int i = 0; i < v.size(); ++i)
    for(int j = 0; j < v.size()-1; ++j)
      if(v[j+1] < v[j])
        swap(v[j+1], v[j]);
}
```

- Advantage: generalized to all kinds of types with []-operator
- Disadvantage: requirements for T are not clear
  - Unfortunately, there is no way of enforcing an interface

  ⇒ Need to comment our function very carefully

  ⇒ Introduce ‘concepts’ as informal interfaces

# Generic Programming

```
/*
    'RandomAccessContainer' concept:
    - t[i] must be a valid expression
    - t[i] must be a valid left-hand-side
    - t.size() must return the size of the container
    - '<' must be defined for all t[i], t[j]
*/

// T must be a model of the RandomAccess concept!
template<typename T>
void bubbleSort(T& v)
{
  for(int i = 0; i < v.size(); ++i)
    for(int j = 0; j < v.size()-1; ++j)
      if(v[j+1] < v[j])
        swap(v[j+1], v[j]);
}
```

# Generic Programming

```
/*
    'ForwardIt' concept: ++, ==, !=
    'ReadWrite' concept: *it is valid lhs
    'Comparable' concept: *it1 < *it2
*/

// Iterator must model ForwardIt, ReadWrite, Comparable
template<typename Iterator>
void bubbleSort(Iterator begin, Iterator end)
{
  for(Iterator it = begin; it != end; ++it)
    for(Iterator it3 = begin, it2 = it3++; it3 != end;
        ++it2, ++it3)
      if(*it3 < *it2)
        swap(*it3, *it2);
}
```

⇒ STL style generic programming

# Enter BGL

# BGL
## Generic Programming

- BGL aims at being extremely versatile and extensible
  - ⇒BGL algorithms should be applicable to any custom graphs that exhibit a minimal interface
  - ⇒generic programming
- BGL also provides graph implementations that model the different concepts

# BGL

## Graph Traversal Concepts

| Concept | refines | types (traits) | expressions | runtime |
|---|---|---|---|---|
| Graph | -- | vertex_descriptor<br>directed_category<br>edge_parallel_category<br>traversal_category | | |
| Incidence Graph | Graph | edge_descriptor<br>out_edge_iterator<br>degree_size_type | source(e,g)<br>target(e,g)<br>out_edges(v,g)<br>out_degree(v,g) | O(1)<br>O(1)<br>O(1)<br>$O(d^-(v))$ |
| Bidirectional Graph | Incidence Graph | in_edge_iterator | in_edges(v,g)<br>in_degree(v,g)<br>degree(v,g) | O(1)<br>$O(d^+(v))$ |
| AdjacencyGraph | Graph | adjacency_iterator | adjacent_vertices(v,g) | O(1) |
| VertexListGraph | Graph | vertex_iterator<br>vertices_size_type | vertices(g)<br>num_vertices(g) | O(1)<br>O(n) |
| EdgeListGraph | Graph | edge_descriptor<br>edge_iterator<br>edges_size_type | edges(g)<br>source(e,g)<br>target(e,g)<br>num_edges(g) | O(1)<br>O(1)<br>O(1)<br>O(m) |
| AdjacencyMatrix | Graph | | edge(u,v,g) | O(1) |

# BGL

## Graph Modification Concepts

| Concept | refines | types (traits) | expressions | O |
|---|---|---|---|---|
| `VertexMutable Graph` | `Graph` | | `add_vertex(g)`<br>`remove_vertex(v,g)` | O(1*)<br>O(m+n) |
| `EdgeMutable Graph` | `Graph` | | `clear_vertex(v,g)`<br>`add_edge(u,v,g)`<br>`remove_edge(u,v,g)`<br>`remove_edge(e,g)` | O(m+n)<br>O(1*)<br>O(m)<br>O(m) |
| `Mutable IncidenceGraph` | `IncidenceG, EdgeMutableG` | | `remove_edge(eiter,g)`<br>`remove_out_edge_if(u,p,g)` | O(1)<br>O($d^-$(v)) |
| `MutableBidirecti onalGraph` | `MutableIncidence G,BidirectionalG` | | `remove_edge(eiter,g)`<br>`remove_out_edge_if(u,p,g)` | O(1)<br>O($d^+$(v)) |
| `PropertyEdgeList Graph` | `Graph` | `property_map <G,T>::type`<br>`proper...`<br>`::const_type` | `get(ptag,g)`<br>`get(ptag,g,x)`<br>`get(ptag,g,x,v)` | O(1)<br>O(1)<br>O(1) |
| `VertexMutable PropertyGraph` | `VertexMutableG, PropertyG` | | `add_vertex(vp,g)` | O(1*) |
| `EdgeMutableGraph PropertyGraph` | `EdgeMutableG, PropertyG` | | `add_edge(u,v,ep,g)` | O(1*) |

# BGL
## Workflow

1. Decide what algorithm you need
2. Check the documentation for the graph concepts required by the algorithm
3. Choose a suitable graph implementation
4. Set-up the graph and invoke algorithm

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# BGL
## Example Algorithm

### topological_sort

```
template <typename VertexListGraph, typename OutputIterator,
          typename P, typename T, typename R>
void topological_sort(VertexListGraph& g, OutputIterator result,
    const bgl_named_params<P, T, R>& params = all defaults)
```

The topological sort algorithm creates a linear ordering of the vertices such that if edge *(u,v)* appears in the graph, then *v* comes before *u* in the ordering. The graph must be a directed acyclic graph (DAG). The implementation consists mainly of a call to `depth_first_search()`.

#### Where Defined:

`boost/graph/topological_sort.hpp`

!!

(note: this is not the whole truth!)

#### Parameters

IN: `VertexListGraph& g`

> A directed acylic graph (DAG). The graph type must be a model of Vertex List Graph and Incidence Graph. If the graph is not a DAG then a `not_a_dag` exception will be thrown and the user should discard the contents of `result` range.
> **Python**: The parameter is named `graph`.

OUT: `OutputIterator result`

> The vertex descriptors of the graph will be output to the `result` output iterator in **reverse** topological order. The iterator type must model Output Iterator.
> **Python**: This parameter is not used in Python. Instead, a Python `list` containing the vertices in topological order is returned.

# BGL
## Example Algorithm

### Named Parameters

UTIL/OUT: `color_map(ColorMap color)`

> This is used by the algorithm to keep track of its progress through the graph. The type `ColorMap` must be a model of Read/Write Property Map and its key type must be the graph's vertex descriptor type and the value type of the color map must model ColorValue.
> **Default:** an iterator_property_map created from a `std::vector` of `default_color_type` of size `num_vertices(g)` and using the `i_map` for the index map.
> **Python**: The color map must be a `vertex_color_map` for the graph.

IN: `vertex_index_map(VertexIndexMap i_map)`

> This maps each vertex to an integer in the range `[0, num_vertices(g))`. This parameter is only necessary when the default color property map is used. The type `VertexIndexMap` must be a model of Readable Property Map. The value type of the map must be an integer type. The vertex descriptor type of the graph needs to be usable as the key type of the map.
> **Default:** `get(vertex_index, g)` Note: if you use this default, make sure your graph has an internal `vertex_index` property. For example, `adjacenty_list` with `VertexList=listS` does not have an internal `vertex_index` property.
> **Python**: Unsupported parameter.

### Complexity

The time complexity is $O(V + E)$. !!

### Example

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# BGL

## some graph alternatives

| type | Graph | models |
|---|---|---|
| BGL classes | adjacency_list | DefaultConstructible, CopyConstructible, Assignable, VertexListGraph, EdgeListGraph, IncidenceGraph, AdjacencyGraph, VertexMutableGraph, EdgeMutableGraph, BidirectionalGraph$^*$, VertexMutablePropertyGraph$^*$, EdgeMutablePropertyGraph$^*$ |
| | adjacency_matrix | VertexListGraph, EdgeListGraph, IncidenceGraph, AdjacencyGraph, AdjacencyMatrix, VertexMutablePropertyGraph, EdgeMutablePropertyGraph |
| BGL adaptors | edge_list | EdgeListGraph |
| | std::vector<EdgeList> | VertexListGraph, IncidenceGraph, AdjacencyGraph |
| custom | [your own] | Whatever you make it support. |

+ ...

# Example

# Example

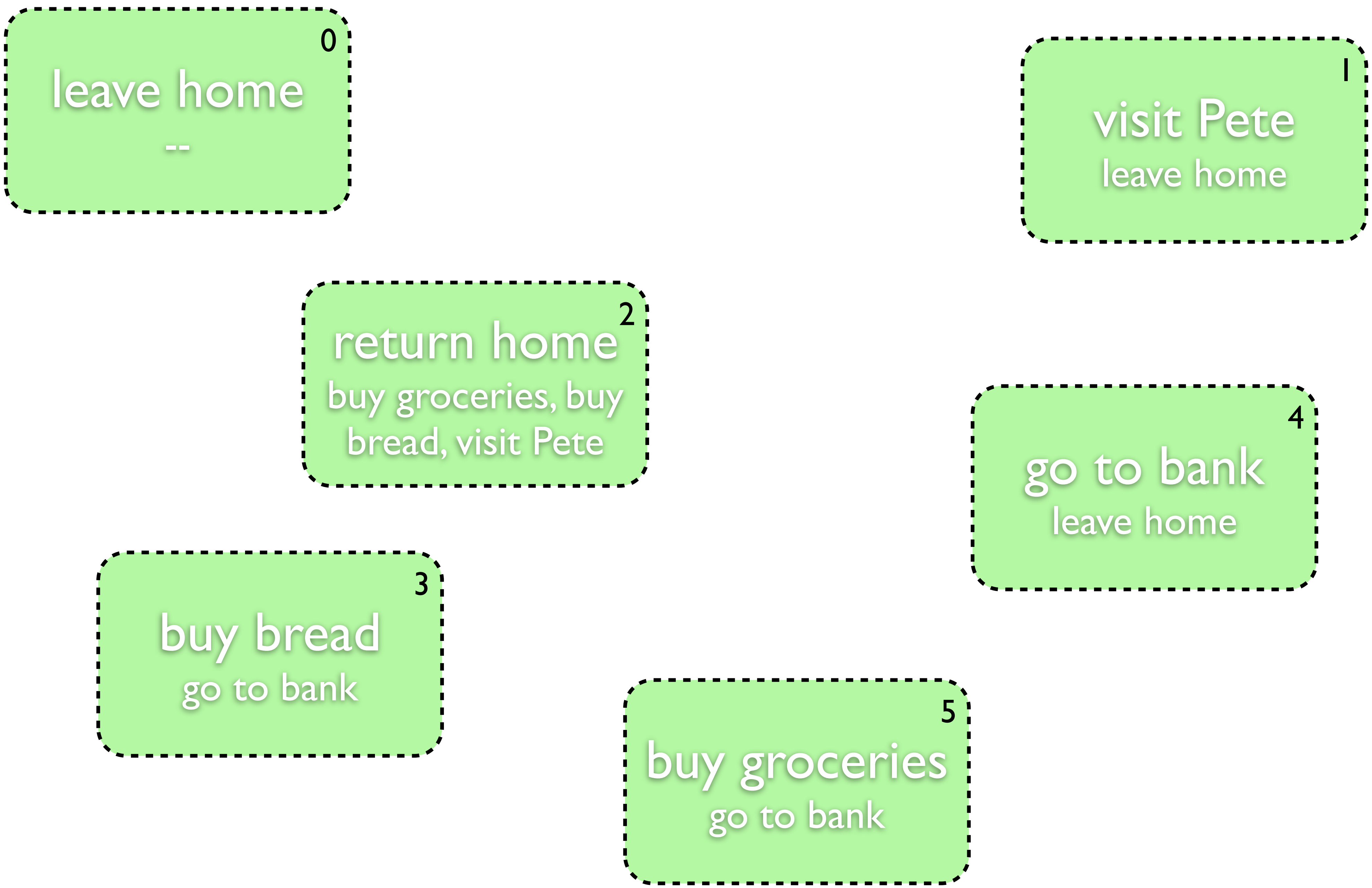
## Problem Statement

Scheduling is important in various contexts: scheduling calculations for CPUs, scheduling processes in buisinesses, scheduling engineering tasks in automated manufactoring.

We consider the general case of conflict-free scheduling of abstract tasks. Every task may depend upon the prior execution of other tasks and may be selected only once these tasks have been performed.

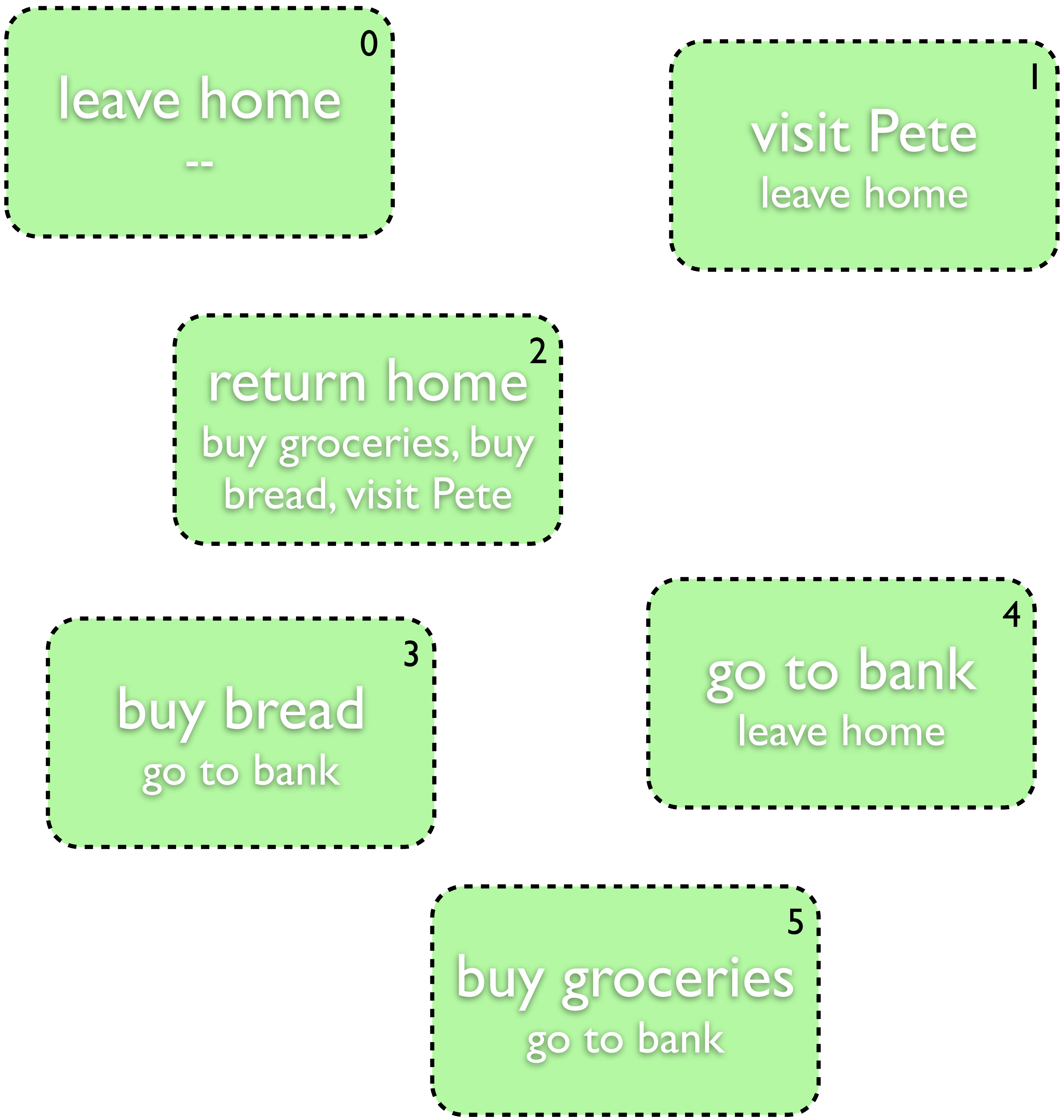
Problem: Find an ordering of the tasks such that all dependencies are respected.

# Example
## Illustrated



# Example

## Illustrated




number of tasks

Input:

6

7

number of dependencies

```
0 1
0 4
1 2
3 2
4 3
4 5
5 2
```

dependencies

# Example
## Workflow

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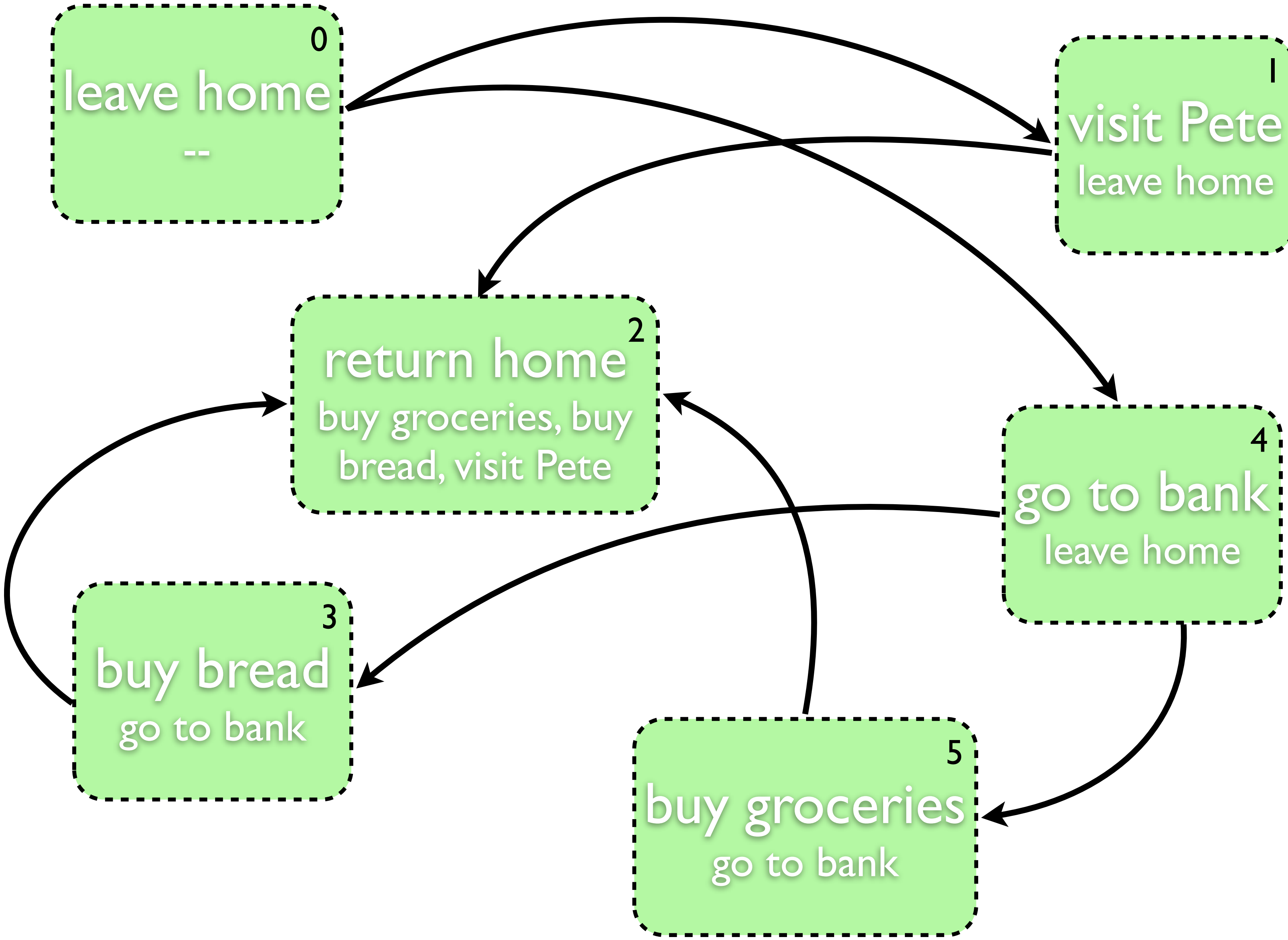
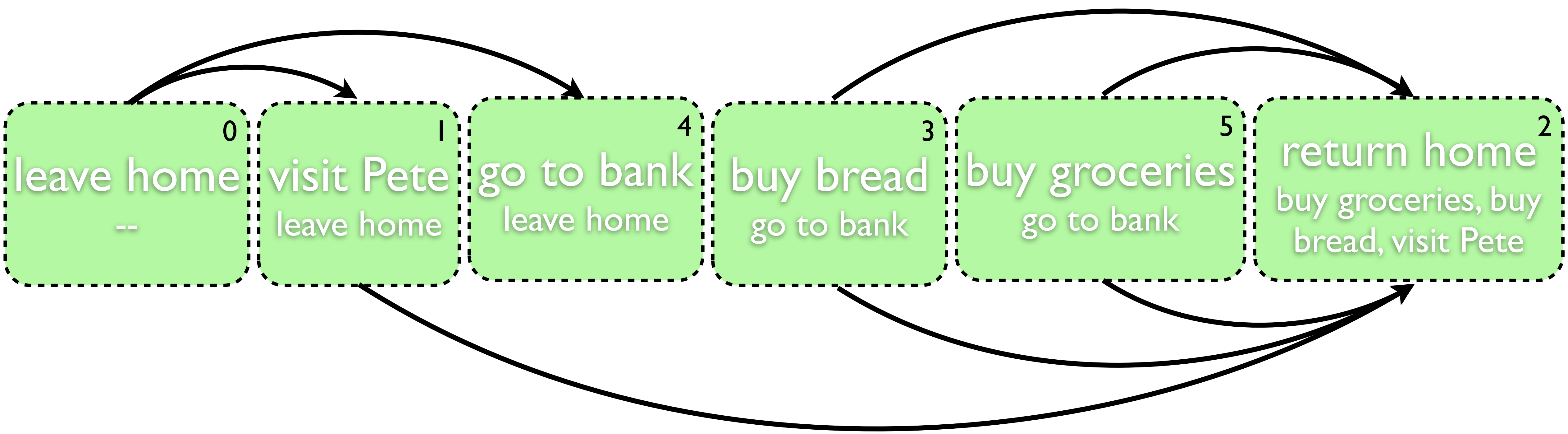
# Example
## Identifying the Underlying Problem



# Example

## Identifying the Underlying Problem




⇒ Topological Sort

# Example
## Workflow

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# Example
## Topological Sort Algorithm

topological sort
requires:
VertexListGraph
IncidenceGraph

### topological_sort

```
template <typename VertexListGraph, typename OutputIterator,
          typename P, typename T, typename R>
void topological_sort(VertexListGraph& g, OutputIterator result,
    const bgl_named_params<P, T, R>& params = all defaults)
```

The topological sort algorithm creates a linear ordering of the vertices such that if edge *(u,v)* appears in the graph, then *v* comes before *u* in the ordering. The graph must be a directed acyclic graph (DAG). The implementation consists mainly of a call to `depth_first_search()`.

### Where Defined:

`boost/graph/topological_sort.hpp`

### Parameters

IN: `VertexListGraph& g`

A directed acylic graph (DAG). The graph type must be a model of Vertex List Graph and Incidence Graph. If the graph is not a DAG then a `not_a_dag` exception will be thrown and the user should discard the contents of `result` range.
**Python**: The parameter is named `graph`.

OUT: `OutputIterator result`

The vertex descriptors of the graph will be output to the `result` output iterator in **reverse** topological order. The iterator type must model Output Iterator.
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## Workflow


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# Example

## Choosing Graph Representation

topological sort requires: VertexListGraph IncidenceGraph

| type | Graph | models |
|---|---|---|
| BGL classes | adjacency_list | DefaultConstructible, CopyConstructible, VertexListGraph, EdgeListGraph, Inciden AdjacencyGraph, VertexMutableGraph, EdgeMutableGraph, BidirectionalGraph*, VertexMutablePropertyGraph*, EdgeMutablePropertyGraph* |
| | adjacency_matrix | VertexListGraph, EdgeListGraph, IncidenceGraph, AdjacencyGraph, AdjacencyMatrix, VertexMutablePropertyGraph, EdgeMutablePropertyGraph |
| BGL adaptors | edge_list | EdgeListGraph |
| | std::vector<EdgeList> | VertexListGraph, IncidenceGraph, AdjacencyGraph |
| custom | [your own] | Whatever you make it support. |

Easy to use!

# Example

## Choosing Graph Representation

Almost always appropriate!

topological sort requires:
VertexListGraph
IncidenceGraph

| type | Graph | models |
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| BGL classes | adjacency_list | DefaultConstructible, CopyConstructible, VertexListGraph, EdgeListGraph, Inciden AdjacencyGraph, VertexMutableGraph, EdgeMutableGraph, BidirectionalGraph*, VertexMutablePropertyGraph*, EdgeMutablePropertyGraph* |
| | adjacency_matrix | VertexListGraph, EdgeListGraph, IncidenceGraph, AdjacencyGraph, AdjacencyMatrix, VertexMutablePropertyGraph, EdgeMutablePropertyGraph |
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# Example
## Workflow

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# Example

## Graph Setup

```
#include <iostream>
#include <boost/graph/adjacency_list.hpp>
using namespace std;
using namespace boost;

typedef adjacency_list<vecS, vecS, directedS> Graph;

int main()
{
  int n, m; cin >> n >> m;
  Graph graph(n);

  for(int i = 0; i < m; ++i)
  {
    int u, v; cin >> u >> v;
    add_edge(u, v, graph);
  }
}
```

# Example

## Invoking BGL

```
...
#include <vector>
#include <boost/graph/topological_sort.hpp>
...

int main()
{
  ...

  vector<int> order(n);
  topological_sort(graph, &order[0]);

  for(int i = n-1; i >= 0; --i)
    cout << order[i] << (i > 0 ? " " : "\n");
}
```

# Summary

# Summary
## Workflow

1. Decide what algorithm you need
2. Check the documentation for the graph concepts required by the algorithm
3. Choose a suitable graph implementation
4. Set-up the graph and invoke algorithm

# The End.