LEMON

Library for Efficient Modeling and Optimization in Networks

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Overview

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   - Algorithms
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   - Shortest Paths
   - Maximum Flows
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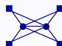
1 Introduction to LEMON

What is LEMON?

- **LEMON** is an abbreviation for

  Library for **E**fficient **M**odeling and **O**ptimization in **N**etworks.
- It is an **open source C++ template library** for optimization tasks related to **graphs and networks**.
- It provides **highly efficient implementations** of common data structures and algorithms.
- It is maintained by the EGRES group at Eötvös Loránd University, Budapest, Hungary.
- `http://lemon.cs.elte.hu`

Sponsors:



Design Goals

- Genericity:
  - clear separation of data structures and algorithms,
  - excessive use of modern software development paradigms.
- Running time efficiency:
  - to be appropriate for using in running time critical applications.
- Ease of use:
  - elegant and convenient interface based on clear design concepts,
  - provide a large set of flexible components,
  - make it easy to implement new algorithms and tools,
  - support easy integration into existing applications.
- Applicability for production use:
  - open source code with a very permissive licensing scheme (Boost 1.0 license).

Motivation

- We missed a tool like that.
  - Source code of commercial libraries cannot be examined or improved.
  - Other open source graph libraries are not well designed and lack sophisticated implementations.
- We observed a need for such a graph library in the (industrial) research.
  - Commercial tools are not always appropriate.
- We wanted something better than the existing ones.
- We wanted to attract more people to applied research.
  - Students participating in the development of LEMON
    - learn programming by implementing new features,
    - get experience in collaborative development,
    - can more easily be involved in other research projects.

LICENSE (same as BOOST)

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...

LEMON Components

- Efficient **data structures** for graphs and related data.
- Flexible and very fast implementations of several combinatorial **algorithms** (graph search, shortest paths, flow and matching problems etc.).
- Input-output support for various graph file formats.
  - An own flexible file format: LGF.
- A uniform and high-level interface for different LP and MIP solvers (GLPK, Clp, Cbc, CPLEX, SoPlex).
- Detailed documentation.
- Build environment.

Graph Structures

- LEMON contains highly efficient graph implementations (both in terms of running time and memory space).
- They have easy-to-use interface.

- Generic design:
  - C++ template programming is heavily used.
  - There are generic graph *concepts* and several graph *implementations* for diverging purposes.
  - The algorithms work with arbitrary graph structures.
  - Users can also write their own graph classes.

Building Graphs

Creating a graph

```
using namespace lemon;
ListDigraph g;
```

Adding nodes and arcs

```
ListDigraph::Node u = g.addNode();
ListDigraph::Node v = g.addNode();
ListDigraph::Arc a = g.addArc(u,v);
```

Removing items

```
g.erase(a);
g.erase(v);
```

Iterators

- The graph structures provide several *iterators* for traversing the nodes and arcs.

Iteration on nodes

```
for (ListDigraph::NodeIt v(g); v != INVALID; ++v) {...}
```

Iteration on arcs

```
for (ListDigraph::ArcIt a(g); a != INVALID; ++a)
for (ListDigraph::OutArcIt a(g,v); a != INVALID; ++a)
for (ListDigraph::InArcIt  a(g,v); a != INVALID; ++a)
```

Note: `INVALID` is a constant, which converts to each and every iterator and graph item type.

Iterators

- Contrary to C++ STL, LEMON iterators are convertible to the corresponding item types without having to use `operator*()`.
- This provides a more convenient interface.
- The program context always indicates whether we refer to the iterator or to the graph item.

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Example: Printing node identifiers

```
for (ListDigraph::NodeIt v(g); v!=INVALID; ++v) {
  std::cout << g.id(v) << std::endl;
}
```

Iterators

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Example: Printing node identifiers

```
for (ListDigraph::NodeIt v(g); v!=INVALID; ++v) {   ← iterator
  std::cout << g.id(v) << std::endl;                ← item
}
```

Maps

- The graph classes represent only the pure structure of the graph.
- All associated data (e.g. node labels, arc costs or capacities) are stored separately using so-called *maps*.

Creating maps

```
ListDigraph::NodeMap<std::string> label(g);
ListDigraph::ArcMap<int> cost(g);
```

Accessing map values

```
label[s] = "source";
cost[e] = 2 * cost[f];
```

Benefits of Graph Maps

- **Efficient.** Accessing map values is as fast as reading or writing an array.
- **Dynamic.** You can create and destruct maps freely.
  - Whenever you need, you can allocate a new map.
  - When you leave its scope, the map will be deallocated automatically.
  - The lifetimes of maps are not bound to the lifetime of the graph.
- **Automatic.** The maps are updated automatically on the changes of the graph.
  - If you add new nodes or arcs to the graph, the storage of the existing maps will be expanded and the new slots will be initialized.
  - If you remove items from the graph, the corresponding values in the maps will be properly destructed.

Map Concepts

- LEMON maps are not just storage classes. They are concepts of any key–value based data access.
- This design provides great flexibility.

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- This design provides great flexibility.
  - Users can write their own maps.

Example: Constant map

```
class MyMap {
public:
  typedef ListDigraph::Arc Key;
  typedef double Value;
  Value operator[](Key k) const { return 3.14; }
};
```

Map Concepts

- LEMON maps are not just storage classes. They are concepts of any key–value based data access.
- This design provides great flexibility.
  - Users can write their own maps.
  - LEMON provides several “lightweight” *map adaptor* classes in addition to the standard graph maps.

Map Adaptors

- A map adaptor class is attached to another map and performs various operations on the original data.
- This is done “on the fly” when the access operations are called.
- The original storage is neither modified nor copied.

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Standard method

```
ListDigraph::ArcMap<int> cost(g);
...  // set arc costs
algorithm(g, cost);
...  // increase arc costs by 100
algorithm(g, cost);
```

Map Adaptors

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- The original storage is neither modified nor copied.

Using map adaptor

```
ListDigraph::ArcMap<int> cost(g);
...  // set arc costs
algorithm(g, cost);
algorithm(g, shiftMap(cost, 100));
```

Algorithms I.

Graph search

- BFS, DFS

Algorithms I.

Graph search

Shortest paths

- Dijkstra (with various heaps)
- Bellman-Ford
- Suurballe

Algorithms I.

Graph search

Shortest paths

Spanning trees

- Kruskal
- Min. cost arborescence

Algorithms I.

Graph search

Shortest paths

Spanning trees

Connectivity

- Connected components
- Strongly connected components
- Topological ordering
- 2-connected components, articulation nodes

Algorithms I.

Graph search

Shortest paths

Spanning trees

Connectivity

Algorithms II.

Network flows

- Maximum flow
- Feasible circulation
- Minimum cost flow
- Minimum cut

Algorithms II.

Network flows

- Maximum flow
  - Preflow push-relabel (with various heuristics)
- Feasible circulation
- Minimum cost flow
- Minimum cut

Algorithms II.

Network flows

- Maximum flow
- Feasible circulation
    - generalized version (push-relabel algorithm)
- Minimum cost flow
- Minimum cut

Algorithms II.

Network flows

- Maximum flow
- Feasible circulation
- Minimum cost flow
  - Cycle-canceling (3 versions)
  - Capacity scaling
  - Cost scaling (3 versions with various heuristics)
  - Network simplex (5 different pivot rules)
- Minimum cut

Algorithms II.

Network flows

- Maximum flow
- Feasible circulation
- Minimum cost flow
- Minimum cut
  - Hao-Orlin
  - Gomory-Hu

Algorithms II.

Network flows

Matching

- Max. cardinality matching
- Max. weighted matching
- Fractional matching

Algorithms II.

Network flows

Matching

Minimum mean cycle

- Karp
- Hartmann-Orlin
- Howard

Algorithms II.

Network flows

Matching

Minimum mean cycle

Planar graphs

- Planar embedding
- Planar drawing

Algorithms II.

Network flows

Matching

Minimum mean cycle

Planar graphs

Auxiliary algorithms

- Radix sort

Algorithms II.

Network flows

Matching

Minimum mean cycle

Planar graphs

Auxiliary algorithms

Others

Data structures

- Graphs and maps
- Path structures
- Priority queues (binary, D-ary, Fibonacci, pairing, radix, bucket, etc. heaps)
- Union-find structures
- Auxiliary data structures

Others

Data structures

Input-output support

- LEMON Graph Format (LGF)
- Other graph formats: DIMACS, Nauty
- EPS exporting

Others

Data structures

Input-output support

General optimization tools

- High-level common interface for LP and MIP solvers

Others

Data structures

Input-output support

General optimization tools

Mersenne-Twister pseudo-random generator

- Best statistical properties and very fast
- Uniform, Gauss, Exponential, Pareto, Weibull, etc. distributions

Others

Data structures

Input-output support

General optimization tools

Mersenne-Twister pseudo-random generator

Auxiliary tools

- Time measuring tools and counters
- Command line argument parser
- etc.

Others

Data structures

Input-output support

General optimization tools

Mersenne-Twister pseudo-random generator

Auxiliary tools

Algorithm Interfaces

Class interface

Function-type interface

Algorithm Interfaces

Class interface

- Complex initializations.
- Flexible execution control:
  - step-by-step execution,
  - multiple execution,
  - custom stop conditions.
- Complex queries.
- The used data structures (maps, heaps, etc.) can be changed.

Function-type interface

Algorithm Interfaces

Class interface

- Complex initializations.
- Flexible execution control.
- Complex queries.
- The used data structures (maps, heaps, etc.) can be changed.

Function-type interface

- Single execution: “*this is the input*”, “*put the results here*”.
- Simpler usage:
  - template parameters do not have to be given explicitly,
  - arguments can be set using *named parameters*,
  - temporary expressions can be passed as reference parameters.
- It provides less flexibility in the initialization, execution and queries.

Using Algorithms

Class interface

```
Dijkstra<ListDigraph> dijk(g, length);
dijk.distMap(dist);


dijk.run(s);


std::cout << dist[t] << std::endl;
```

Using Algorithms

Class interface

```
Dijkstra<ListDigraph> dijk(g, length);
dijk.distMap(dist);

dijk.init();
dijk.addSource(s1); dijk.addSource(s2);
dijk.start();

std::cout << dist[t] << std::endl;
```

Using Algorithms

Class interface

```
Dijkstra<ListDigraph> dijk(g, length);
dijk.distMap(dist);

dijk.init();
dijk.addSource(s1); dijk.addSource(s2);
dijk.start();

std::cout << dist[t] << std::endl;
```

Function-type interface

```
dijkstra(g, length).distMap(dist).run(s);
```

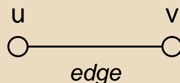
Using Algorithms

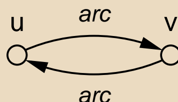
Example: Number of connected components

```
template <typename GR>
int numberOfComponents(const GR &g) {
  int c = 0;
  Bfs<GR> bfs(g);
  bfs.init();
  for (typename GR::NodeIt v(g); v != INVALID; ++v) {
    if (!bfs.reached(v)) {
      c++;
      bfs.addSource(v);
      bfs.start();
    }
  }
  return c;
}
```

Undirected Graphs

- An *undirected* graph is also considered as a *directed* one at the same time.
- Each undirected *edge* can also be regarded as two oppositely directed *arcs*.
- As a result, each algorithm working on a directed graph naturally runs on an undirected graph, as well.





Graph Adaptors

- LEMON also provides *graph adaptor* classes (similarly to map adaptors).
- They serve for considering other graphs in different ways using the storage and operations of the original structure.
- Another view of a graph can be obtained without having to modify or copy the actual storage.
- This technique yields convenient and elegant codes.

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Working with the original graph

```
algorithm(g);
```

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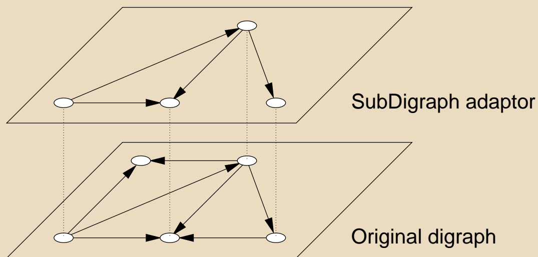
- Another view of a graph can be obtained without having to modify or copy the actual storage.
- This technique yields convenient and elegant codes.

Working with the reverse oriented graph

```
algorithm(reverseDigraph(g));
```

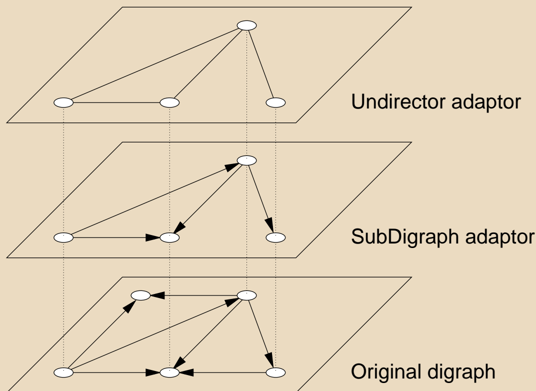
Using Graph Adaptors

Obtaining a subgraph



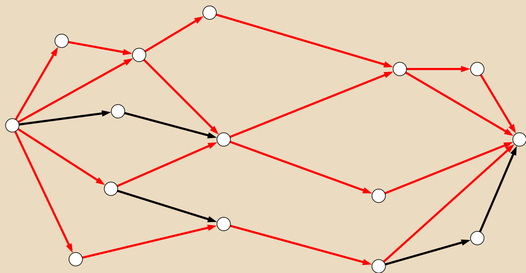
Using Graph Adaptors

Combining adaptors



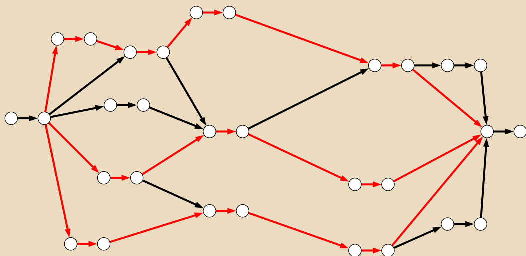
Example: Finding Disjoint Paths

- The maximum number of *arc disjoint* paths between two nodes can be found by computing a maximum flow using uniform arc capacities.



Example: Finding Disjoint Paths

- For finding *node disjoint* paths, the maximum flow algorithm can be used in conjunction with the `SplitNodes` adaptor.
- It splits each node into an *in-node* and an *out-node*.



LP Interface

- LEMON provides a convenient, high-level interface for several *linear programming* (LP) and *mixed integer programming* (MIP) solvers.
- Currently supported:

GLPK:	open source (GNU license)
Clp, Cbc:	open source (COIN-OR LP and MIP solvers)
CPLEX:	commercial
SoPlex:	academic license

- Additional wrapper classes for other solvers can be implemented easily.

Using the LP Interface

Building and solving an LP problem

```
Lp lp;
Lp::Col x1 = lp.addCol();
Lp::Col x2 = lp.addCol();

lp.max();
lp.obj(10 * x1 + 6 * x2);

lp.addRow(0 <= x1 + x2 <= 100);
lp.addRow(2 * x1 <= x2 + 32);

lp.colLowerBound(x1, 0);

lp.solve();

std::cout << "Solution:  " << lp.primal() << std::endl;
std::cout << "x1 = " << lp.primal(x1) << std::endl;
std::cout << "x2 = " << lp.primal(x2) << std::endl;
```

Using the LP Interface

Building and solving an LP problem

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```

Mathematical formulation

$$\max 10x_1 + 6x_2$$

$$0 \leq x_1 + x_2 \leq 100$$

$$2x_1 \leq x_2 + 32$$

$$x_1 \geq 0$$

Example graph

```
@nodes
label coordinate
0     (20,100)
1     (40,120)
...
41    (600,100)
@arcs
            label length
0     1     0     16
0     2     1     12
2     12    2     20
...
36    41    123   21
@attributes
source 0
caption "A shortest path problem"
```

LGF – LEMON Graph Format

Example graph

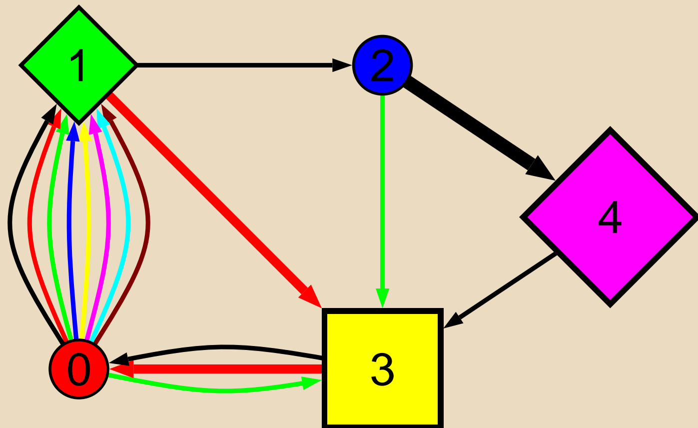
```
@nodes
label coordinate
0     (20,100)
...
41    (600,100)
@arcs
          label length
0    1    0    16
...
36   41   123  21
@attributes
source 0
caption "A shortest path problem"
```

Reading the graph

```
digraphReader(g, "input.lgf")
   .nodeMap("coord", coord)
   .arcMap("length", length)
   .attribute("caption", title)
   .node("source", src)
   .run();
```

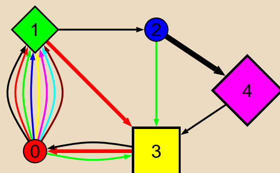
Postscript Exporting

EPS example



Postscript Exporting

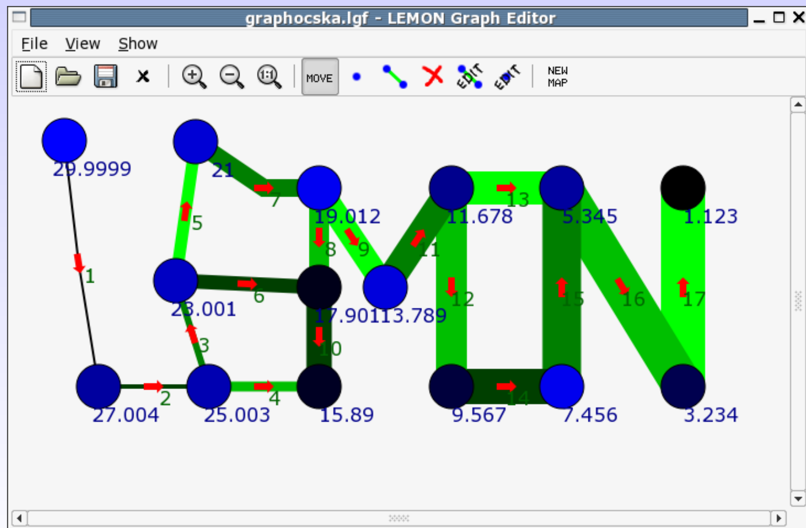
EPS example



Exporting to EPS

```
graphToEps(g, "graph.eps")
  .copyright("(c) 2003-2010 LEMON Project")
  .title("Sample EPS figure").coords(coords)
  .nodeScale(2).nodeSizes(sizes).nodeTexts(id).nodeTextSize(3)
  .nodeColors(composeMap(palette, colors)).nodeShapes(shapes)
  .arcColors(composeMap(palette, acolors))
  .arcWidthScale(.3).arcWidths(widths)
  .drawArrows().arrowWidth(1).arrowLength(1)
  .enableParallel().parArcDist(1)
  .run();
```

gLEMON – A Graph Editor for LEMON



Technical Support

- Extensive documentation:
  - Reference manual (generated using Doxygen)
  - Tutorial
- Mailing lists.
- Version control (Mercurial).
- Bug tracker system (Trac).
- Build environment:
  - Autotools (Linux)
  - CMake (Windows)
- Support of different compilers:
  - GNU C++
  - Intel C++
  - IBM xlC
  - Microsoft Visual C++

Users of LEMON

- Several projects at ELTE and BME, Budapest
- ZIB, Berlin
- Ericsson Research
- CPqD, Brazil
- Personal users
- etc.

- LEMON is a part of the COIN-OR software collection.
  `http://www.coin-or.org/`

User Reviews

"I use LEMON to solve the problem of tangent plane orientation in surface reconstruction... In my project I decided to use LEMON because it was easier to understand and use than other projects like "boost" and I also found that it runs fast."

"I searched long and hard for a graph library I could use. Yours was the only library that is robust, has documentation that makes sense, and is not obfuscated by excessive use of templates. For example, I spent quite some time with the Boost Graph Library and got nowhere. It builds generality upon generality."

2 Performance

Performance

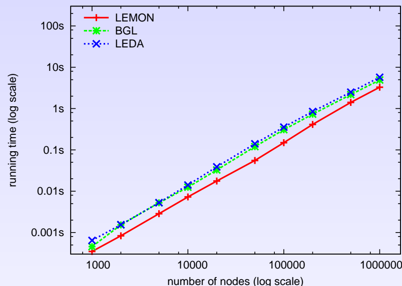
The performance of **LEMON** is compared to its major competitors:

- **BGL** – Boost Graph Library
- **LEDA** library

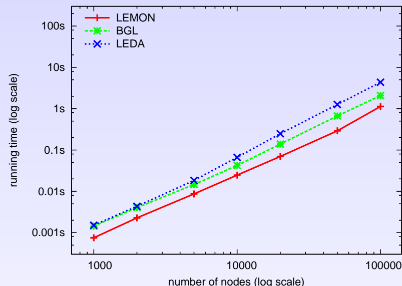
VS

Shortest Paths

Benchmark results for **Dijkstra's algorithm**:



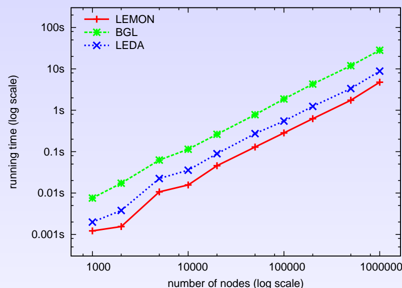
Sparse networks



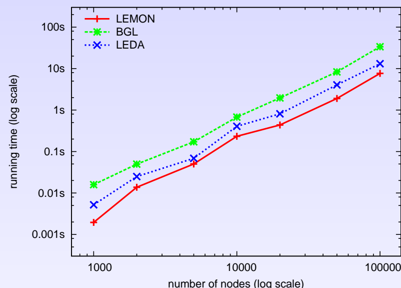
Dense networks

Maximum Flows

Benchmark results for the **push-relabel algorithm**:



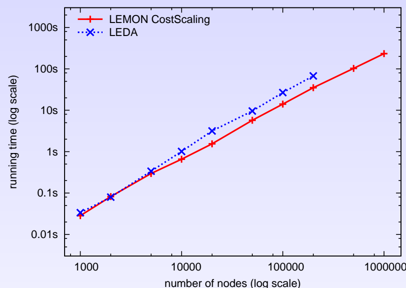
Sparse networks



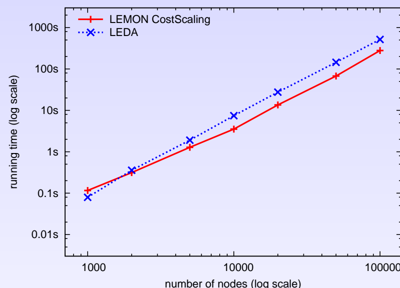
Dense networks

Minimum Cost Flows

Benchmark results for **minimum cost flow algorithms**:



Sparse networks

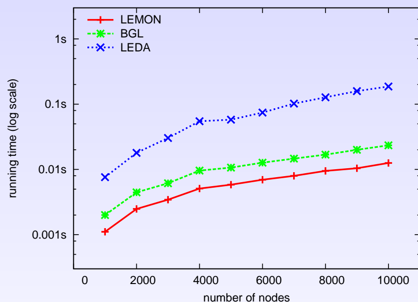


Dense networks

Note: BGL does not provide a minimum cost flow algorithm, but it has been among the plans of the developers for a long time.

Planar Embedding

Benchmark results for **planar embedding algorithms**:



Section 3

3 History and Statistics

History of LEMON

2003–2007 **LEMON 0.x** series

- Development versions without stable API.
- Latest release: LEMON 0.7.

2008– **LEMON 1.x** series

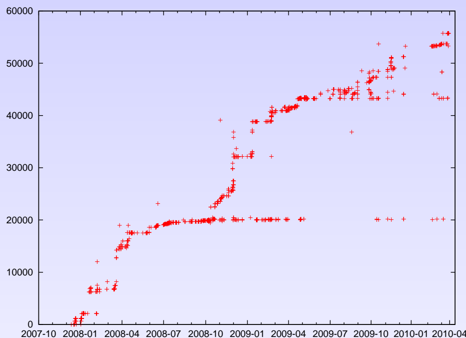
- Stable releases ensuring full backward compatibility.
- Major versions:

  2008-10-13 **LEMON 1.0** released
  2009-05-13 **LEMON 1.1** released
  2010-03-19 **LEMON 1.2** released

2009-03-27 LEMON joins to the **COIN-OR** initiative.

- `http://www.coin-or.org/`

SLOC – Source Lines of Code



	lemon	test	tools	scripts	demo	Total	
C++	45,032	8340	983		238	**54,593**	(97.98%)
Python				513		**513**	(0.92%)
other			130	478		**608**	(1.09%)
Total:	45,032	8340	1113	991	238	**55,714**	

4 Summary

Summary

- LEMON is a **highly efficient** C++ graph template library providing **convenient** and **flexible** components.
- It is **open source** with a very **premissive license**.
- LEMON turned out to be significantly more efficient than its two major competitors, BGL and LEDA.
- Therefore, LEMON is favorable for both research and development in the areas of combinatorial optimization and network design.

The End

Thank you for the attention!

`http://lemon.cs.elte.hu`