

Graph Library: Comparison

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1 Getting Started

This paper is one of several interrelated papers for a proposed Graph Library for the Standard C++ Library. The Table 1 describes all the related papers.

Paper	Status	Description
P1709	Inactive	Original proposal, now separated into the following papers.
P3126	Active	Overview , describes the big picture of what we are proposing.
P3127	Active	Background and Terminology provides the motivation, theoretical background, and terminology used across the other documents.
P3128	Active	Algorithms covers the initial algorithms as well as the ones we'd like to see in the future.
P3129	Active	Views has helpful views for traversing a graph.
P3130	Active	Graph Container Interface is the core interface used for uniformly accessing graph data structures by views and algorithms. It is also designed to easily adapt to existing graph data structures.
P3131	Active	Graph Containers describes a proposed high-performance compressed_graph container. It also discusses how to use containers in the standard library to define a graph, and how to adapt existing graph data structures.
P3337	Active	Comparison to other graph libraries on performance and usage syntax.

Table 1: Graph Library Papers

Reading them in order will give the best overall picture. If you're limited on time, you can use the following guide to focus on the papers that are most relevant to your needs.

Reading Guide

- If you're **new to the Graph Library**, we recommend starting with the *Overview* ([P3126](#)) paper to understand the focus and scope of our proposals. You'll also want to check out it stacks up against other graph libraries in performance and usage syntax in the *Comparison* ([P3337](#)) paper.
- If you want to **understand the terminology and theoretical background** that underpins what we're doing, you should read the *Background and Terminology* ([P3127](#)) paper.
- If you want to **use the algorithms**, you should read the *Algorithms* ([P3128](#)) and *Graph Containers* ([P3131](#)) papers. You may also find the *Views* ([P3129](#)) and *Graph Container Interface* ([P3130](#)) papers helpful.
- If you want to **write new algorithms**, you should read the *Views* ([P3129](#)), *Graph Container Interface* ([P3130](#)), and *Graph Containers* ([P3131](#)) papers. You'll also want to review existing implementations in the reference library for examples of how to write the algorithms.
- If you want to **use your own graph data structures**, you should read the *Graph Container Interface* ([P3130](#)) and *Graph Containers* ([P3131](#)) papers.

2 Revision History

D3337r0

- New paper comparing the Graph Library to the NWGraph and Boost Graph Libraries on performance and usage syntax.

3 Naming Conventions

Table 2 shows the naming conventions used throughout the Graph Library documents.

Template Parameter	Type Alias	Variable Names	Description
G			Graph
	<code>graph_reference_t<G></code>	<code>g</code>	Graph reference
GV		<code>val</code>	Graph Value, value or reference
EL		<code>el</code>	Edge list
V	<code>vertex_t<G></code> <code>vertex_reference_t<G></code>	<code>u,v,x,y</code>	Vertex Vertex reference. <code>u</code> is the source (or only) vertex. <code>v</code> is the target vertex.
VId	<code>vertex_id_t<G></code>	<code>uid,vid,seed</code>	Vertex id. <code>uid</code> is the source (or only) vertex id. <code>vid</code> is the target vertex id.
VV	<code>vertex_value_t<G></code>	<code>val</code>	Vertex Value, value or reference. This can be either the user-defined value on a vertex, or a value returned by a function object (e.g. <code>VVF</code>) that is related to the vertex.
VR	<code>vertex_range_t<G></code>	<code>ur,vr</code>	Vertex Range
VI	<code>vertex_iterator_t<G></code>	<code>ui,vi</code>	Vertex Iterator. <code>ui</code> is the source (or only) vertex.
		<code>first,last</code>	<code>vi</code> is the target vertex.
VVF		<code>vvf</code>	Vertex Value Function: <code>vvf(u) → vertex value</code> , or <code>vvf(uid) → vertex value</code> , depending on requirements of the consume algorithm or view.
VProj		<code>vproj</code>	Vertex info projection function: <code>vproj(x) → vertex_info<VId,VV></code> .
	<code>partition_id_t<G></code>	<code>pid</code>	Partition id.
		<code>P</code>	Number of partitions.
PVR	<code>partition_vertex_range_t<G></code>	<code>pur,pvr</code>	Partition vertex range.
E	<code>edge_t<G></code> <code>edge_reference_t<G></code>	<code>uv,vw</code>	Edge Edge reference. <code>uv</code> is an edge from vertices <code>u</code> to <code>v</code> . <code>vw</code> is an edge from vertices <code>v</code> to <code>w</code> .
EV	<code>edge_value_t<G></code>	<code>val</code>	Edge Value, value or reference. This can be either the user-defined value on an edge, or a value returned by a function object (e.g. <code>EVF</code>) that is related to the edge.
ER	<code>vertex_edge_range_t<G></code>		Edge Range for edges of a vertex
EI	<code>vertex_edge_iterator_t<G></code>	<code>uvi,vwi</code>	Edge Iterator for an edge of a vertex. <code>uvi</code> is an iterator for an edge from vertices <code>u</code> to <code>v</code> . <code>vwi</code> is an iterator for an edge from vertices <code>v</code> to <code>w</code> .
EVF		<code>evf</code>	Edge Value Function: <code>evf(uv) → edge value</code> , or <code>evf(eid) → edge value</code> , depending on the requirements of the consuming algorithm or view.
EProj		<code>eproj</code>	Edge info projection function: <code>eproj(x) → edge_info<VId,Sourced,EV></code> .

Table 2: Naming Conventions for Types and Variables

4 Syntax Comparison

We refer to the reference implementation associated with this proposal as **graph-v2**. In this section, we provide a usage syntax comparison of several graph algorithms in Tier 1 of P3128 against the equivalent implementations in **BGL** [1] and the more recent **NWGraph** [2, 3]. These algorithms are breadth-first search (BFS, Figure 1), connected components (CC, Figure 2), single source shortest paths (SSSP, Figure 3), and triangle counting (TC, Figure 4). We take these algorithms from the GAP Benchmark Suite [4]. We defer to later sections any discussion of underlying implementation details and resulting performance.

Unlike **BGL**, **graph-v2** does not specify edge direction as a graph property. If a graph in **graph-v2** implemented by `container::compressed_graph` is undirected, then it will contain distinct edges in both directions. **BGL** has a `boost::graph::undirectedS` property which can be used in the `boost::graph::adjacency_matrix` class to specify an undirected graph, but not in the `boost::graph::compressed_sparse_row_graph` class. Thus in Figures 1-4, the **BGL** graph type always includes `boost::graph::directedS`. Similar to **graph-v2**, undirected graphs must contain the edges in both directions.

Intermediate data structures (e.g., edge lists) will be needed to construct the compressed graph structures. In order to focus on the differences in algorithm syntax, we omit code which populates the graph data structures. In the following subsections, we address the syntax differences for each of these algorithms.

<pre>using namespace boost; using G = compressed_sparse_row_graph< directedS, no_property, no_property>; using VId = graph_traits<G>::vertex_descriptor; G g; //populate g vector<VId> parents(num_vertices(g)); auto vis = make_bfs_visitor(make_pair(record_predecessors(parents.begin(), on_tree_edge()))); breadth_first_search(g, vertex(0, g), visitor(vis));</pre>	<pre>using namespace std; using namespace graph; using G = container::compressed_graph< void, void, void, uint32_t, uint32_t>; using VId = vertex_id_t<G>; G g; // populate g vector<VId> parents(size(vertices(g))); auto bfs = edges_breadth_first_search_view<G,void,true>(g, 0); for (auto&& [uid, vid, uv] : bfs) { parents[vid] = uid; }</pre>
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Figure 1: Breadth-First Search Syntax Comparison

<pre>using namespace std; using namespace boost; using G = compressed_sparse_row_graph< directedS, no_property, no_property>; G g; //populate g vector<size_t> c(num_vertices(g)); //components size_t num = connected_components(g, &c[0]);</pre>	<pre>using namespace std; using namespace graph; using G = container::compressed_graph< void, void, void, uint32_t, uint32_t>; G g; //populate g vector<size_t> c(size(vertices(g))); //components size_t num = connected_components(g, c);</pre>
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Figure 2: Connected Components Syntax Comparison

<pre> using namespace std; using namespace boost; using G = compressed_sparse_row_graph< directedS, no_property, property<edge_weight_t, int>>; using VId = graph_traits<G>::vertex_descriptor; G g; //populate g vector<VId> p(num_vertices(g)); //predecessors vector<int> d(num_vertices(g)); //distances property_map< graph_t, edge_weight_t >::type weightmap = get(edge_weight, g); dijkstra_shortest_paths(g, vertex(0, g), predecessor_map(make_iterator_property_map(p.begin(), get(vertex_index, g))). distance_map(make_iterator_property_map(d.begin(), get(vertex_index, g)))); </pre>	<pre> using namespace std; using namespace graph; using G = container::compressed_graph< int, void, void, uint32_t, uint32_t>; using VId = vertex_id_t<G>; G g; //populate g vector<VId> p(size(vertices(g))); //predecessors vector<int> d(size(vertices(g))); //distances init_shortest_paths(distance, predecessors); auto weight_fn = [&g](graph::edge_reference_t<graph_type> uv) -> int { return edge_value(g, uv); }; dijkstra_shortest_paths(g, 0, d, p, weight_fn); </pre>
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Figure 3: Single Source Shortest Paths Syntax Comparison

4.1 Breadth-First Search

BFS is often described as a graph algorithm, though a BFS traversal by itself does not actually perform any task. In reality, it is a data access pattern which specifies an order vertices and edges should be processed by some higher level algorithm. **BGL** provided a very customizable interface to this data access pattern through the use of visitors which allows users to customize function calls during BFS events. For example `discover_vertex` is called when a vertex is encountered for the first time; `examine_vertex` is called when a vertex is popped from the queue; `examine_edge` is called on each edge of a vertex when it is discovered, etc.

This capability is very powerful but often cumbersome if the BFS traversal simply requires vertex and edge access upon visiting. For this reason **graph-v2** provides a simple, range-based-for loop BFS traversal called a view. Figure 1 compares the most simple **BGL** BFS visitor against the range-based-for loop implementation. The authors of this proposal acknowledge that some power users still want the full customization provided by visitors, and we plan to add them to this proposal.

4.2 Connected Components

There is very little difference in the connected component interfaces.

4.3 Single Source Shortest Paths

Of the four algorithms discussed here, only SSSP makes use of some edge property, in this case distance. Along with the input edge property, the algorithm also associates with every vertex a distance from the start vertex, and a predecessor vertex to store the shortest path. In Figure 3 we see that **BGL** requires property maps to lookup edge and vertex properties. These property maps are tightly coupled with the graph data structures. We

<pre> using namespace boost; using G = compressed_sparse_row_graph< directedS, no_property, no_property>; using VId = graph_traits<G>::vertex_descriptor; G g; //populate g size_t count{0}; for(size_t i = 0; i < N; i++) { VId cur = vertex(i, g); count += num_triangles_on_vertex(g, cur); } count /= 6; </pre>	<pre> using namespace graph; using G = container::compressed_graph< void, void, void, uint32_t, uint32_t>; G g; //populate g size_t count = triangle_count(g); </pre>
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Figure 4: Triangle Counting Syntax Comparison

propose properties be stored external to the graph. For edge properties we provide a weight lambda function to the algorithm to lookup distance from the `edge_reference_t`.

4.4 Triangle Counting

BGL does not contain a global triangle counting similar to the one proposed by **graph-v2**. Instead we must iterate through the vertices counting the number of triangles on every vertex, and adjust for overcounting at the end.

5 Performance Comparison

5.1 Experimental Setup

To evaluate the performance of this proposed library, we compare its reference implementation (**graph-v2**) against **BGL** and **NWGraph** on a subset of the GAP Benchmark Suite[5]. This comparison includes four of the five GAP algorithms that are in the tier 1 algorithm list of this proposal: triangle counting (TC), connected components (CC), breadth-first search (BFS), and single-source shortest paths (SSSP). Table 3 summarizes the graphs specified by the GAP benchmark. These graphs were chosen to be large but still fit on shared memory machines and have edge counts in the billions. We compare to BGL because it the commonly used sequential C++ graph library as described above. **NWGraph** was implemented with many of the ideas of this proposal in mind, and we expect very similar performance between **NWGraph** and this reference implementation.

Name	Description	#Vertices (M)	#Edges (M)	Degree Distribution	(Un)directed	References
road	USA road network	23.9	57.7	bounded	undirected	[6]
Twitter	Twitter follower links	61.6	1,468.4	power	directed	[7]
web	Web crawl of .sk domain	50.6	1,930.3	power	directed	[8]
kron	Synthetic graph	134.2	2,111.6	power	undirected	[9]
urand	Uniform random graph	134.2	2,147.5	normal	undirected	[10]

Table 3: Summary of GAP Benchmark Graphs

The **NWGraph** authors published a similar comparison to BGL[3] in which they demonstrated performance improvement of **NWGraph** over BGL. To simplify experimental setup, we rerun these new experiments using the same machine used in[3], (compute nodes consisting of two Intel® Xeon® Gold 6230 processors, each with 20 physical cores running at 2.1 GHz, and 188GB of memory per processor). **NWGraph** and **graph-v2** were compiled with gcc 13.2 using -Ofast -march=native compilation flags.

Even though **NWGraph** contains an implementation of Dijkstra, the SSSP results in [3] were based on delta-stepping. For this comparison, **graph-v2** and **NWGraph** both use Dijkstra. The **NWGraph** implementations also used a version of SSSP which did not compute a predecessor map, only providing the final distances. **graph-v2** provides SSSP without predecessors called *dijkstra_shortest_distances* which is similar to the Dijkstra in Figure 3 with the predecessor argument omitted. **BGL** can also compute shortest distances only by omitting the predecessor map. We use the shortest distance version for these experiments.

The **NWGraph** and **graph-v2** implementation of CC is based on the Afforest [11] algorithm. While BFS and SSSP implementations are very similar for **NWGraph** and **graph-v2**, the latter contains support for event-based visitors. If this functionality is not required it should be optimized out and not incur a performance penalty, but we seek to verify this experimentally. **NWGraph** and **graph-v2** contain similar implementations of triangle counting which perform a set intersection of the neighbor list of vertices u and v , only if v is a neighbor of u . By first performing a lexicographic sort of the vertex ids of the adjacency structure, the set intersection is limited to neighbors with vertex ids greater than u and v , or equivalently the upper triangular portion of the adjacency matrix. Table 4 summarizes our GAP benchmark results for **graph-v2** compared to **BGL** and **NWGraph**.

5.2 Experimental Analysis

BFS results are consistent between the three implementations, except for the kron graph where **graph-v2** is 2.4x faster than **NWGraph** and 3.4x faster than **BGL**.

CC results are consistent between **NWGraph** and **graph-v2**, which are both much faster than **BGL** on twitter, kron, and urand. This is reasonable as **BGL** is using a simple breadth-first search based CC algorithm while the other two implementations use the Afforest algorithm. Of the four algorithms, CC shows the closest agreement between **NWGraph** and **graph-v2**.

SSSP results are more mixed, with differing performance on twitter and kron. Interestingly of the algorithms we profile, this is the only one where **BGL** is often faster than the other implementations, faster than **graph-v2** by

Algorithm	Library	road	twitter	kron	web	urand
BFS	BGL	1.09s	12.11s	54.80s	5.52s	73.26s
	NWGraph	0.91s	11.25s	38.86s	2.37s	64.63s
	graph-v2	1.39s	8.54s	16.34s	3.52s	62.75s
CC	BGL	1.36s	21.96s	81.18s	6.64s	134.23s
	NWGraph	1.05s	3.77s	10.16s	3.04s	36.59s
	graph-v2	0.78s	2.81s	8.37s	2.23s	33.75s
SSSP	BGL	4.03s	47.89s	167.20s	28.29s	OOM
	NWGraph	3.63s	109.37s	344.12s	35.58s	400.23s
	graph-v2	4.22s	79.75s	211.37s	33.87s	493.15s
TC	BGL	1.34s	>24H	>24H	>24H	4425.54s
	NWGraph	0.41s	1327.63s	6840.38s	131.47s	387.53s
	graph-v2	0.17s	459.08s	2357.95s	50.04s	191.36s

Table 4: GAP Benchmark Performance: Time for GAP benchmark algorithms is shown for **BGL**, **NWGraph**, **graph-v2**

1.7x on twitter and 1.3x on kron, though failing by running out of memory on urand.

TC performance from the naïve **BGL** implementation is far slower than the adjacency matrix set intersection used by **NWGraph** and **graph-v2**. Since the same triangle is counted 6 times in **BGL**, we expect at least that much of a slowdown, but in fact the slowdown is often much worse. However the TC results are concerning because the **graph-v2** performance is around 2x that of **NWGraph**. We plan to review the implementation details to discover the cause of this discrepancy.

6 Memory Allocation

Unlike existing STL algorithms, the graph algorithms we propose here will often require their own memory allocations. Table 5 records the internal memory allocations required for our implementations of the GAP Benchmark algorithms where relevant. It is important to note that the memory usage is not prescribed by the algorithm interface in P3128, and is ultimately up to the library implementer. Some memory use, such as the queues in BFS and SSSP, will probably be common to most implementations. However, the color map in BFS and the reindex map in CC (used to ensure the resulting component indices are contiguous) could potentially be avoided.

Algorithm	Required Member Data	Max Size
BFS	queue	$O(V)$
	color map	V
CC	reindex map	$O(components)$
SSSP	priority queue	$O(E)$
TC	None	NA

Table 5: Memory Allocations of GAP Benchmark Algorithm Implementations

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References

- [1] J. G. Siek, L.-Q. Lee, and A. Lumsdaine, *The Boost Graph Library: User Guide and Reference Manual*. Addison-Wesley Professional, Dec. 2001.
- [2] A. Lumsdaine, L. D'Alessandro, K. Deweese, J. Firoz, T. Liu, S. McMillan, P. Ratzloff, and M. Zalewski, "Nwgraph: A library of generic graph algorithms and data structures in c++20." <https://drops.dagstuhl.de/opus/volltexte/2022/16259/>.
- [3] A. Lumsdaine, L. D'Alessandro, K. Deweese, J. Firoz, T. Liu, S. McMillan, P. Ratzloff, and M. Zalewski, "Nwgraph library code." <https://github.com/pnnl/NWGraph>.
- [4] S. Beamer, K. Asanović, and D. Patterson, "The gap benchmark suite," *arXiv preprint arXiv:1508.03619*, 2015.
- [5] A. Azad, M. M. Aznaveh, S. Beamer, M. P. Blanco, J. Chen, L. D'Alessandro, R. Dathathri, T. Davis, K. Deweese, J. Firoz, H. A. Gabb, G. Gill, B. Hegyi, S. Kolodziej, T. M. Low, A. Lumsdaine, T. Manlaibaatar, T. G. Mattson, S. McMillan, R. Peri, K. Pingali, U. Sridhar, G. Szarnyas, Y. Zhang, and Y. Zhang, "Evaluation of graph analytics frameworks using the gap benchmark suite," in *2020 IEEE International Symposium on Workload Characterization (IISWC)*, pp. 216–227, 2020.
- [6] "9th DIMACS implementation challenge - Shortest paths.." <http://www.dis.uniroma1.it/challenge9/>, 2006.
- [7] H. Kwak, C. Lee, H. Park, and S. Moon, "What is Twitter, a social network or a news media?," *WWW*, 2010.
- [8] P. Boldi and S. Vigna, "The WebGraph framework I: Compression techniques," *WWW*, pp. 595–601, 2004.
- [9] R. C. Murphy, K. B. Wheeler, B. W. Barrett, and J. A. Ang, "Introducing the Graph 500," in *Cray User's Group*, CUG, 2010.
- [10] P. Erdős and A. Rényi, "On random graphs. I," *Publicationes Mathematicae*, vol. 6, pp. 290–297, 1959.
- [11] M. Sutton, T. Ben-Nun, and A. Barak, "Optimizing parallel graph connectivity computation via subgraph sampling," in *IPDPS*, pp. 12–21, IEEE, 2018.