Performance analysis and optimization of C++ standard libraries

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Suboptimal basic_streambuf::xsgetn (libc++)

```
template <class _CharT, class _Traits>
streamsize
basic_streambuf<_CharT, _Traits>::xsgetn(char_type* __s, streamsize __n)
{
    const int_type __eof = traits_type::eof();
    int_type __c;
    streamsize __i = 0;
    for (;__i < __n; ++__i, ++__s) {
        if (__ninp_ < __einp_)
            *__s = *__ninp_++;
        else if ((__c = uflow()) != __eof)
            *__s = traits_type::to_char_type(__c);
        else
            break;
    }
    return __i;
}
```

Optimized basic_streambuf::xsgetn

```
// After
template <class _CharT, class _Traits>
streamsize
basic_streambuf<_CharT, _Traits>::xsgetn(char_type* __s, streamsize __n) {
    const int_type __eof = traits_type::eof();
    int_type __c;
    streamsize __i = 0;
    while(__i < __n) {
        if (__ninp_ < __einp_) {
            const streamsize __len = _VSTD::min(__einp_ - __ninp_, __n - __i);
            traits_type::copy(__s, __ninp_, __len);
            __s +=  __len;
            __i +=  __len;
            this->gbump(__len);
        }
        else if ((__c = uflow()) != __eof) {
            *__s = traits_type::to_char_type(__c);
            ++__s;
            ++__i;
        }
        else
            break;
    }
    return __i;
}
```

```
// Before
template <class _CharT, class _Traits>
streamsize
basic_streambuf<_CharT, _Traits>::xsgetn(char_type* __s,
streamsize __n)
{
    const int_type __eof = traits_type::eof();
    int_type __c;
    streamsize __i = 0;
    for (;__i < __n; ++__i, ++__s) {
        if (__ninp_ < __einp_)
            *__s = *__ninp_++;
        else if ((__c = uflow()) != __eof)
            *__s = traits_type::to_char_type(__c);
        else
            break;
    }
    return __i;
}
```

Performance improvements

valgrind profile of a synthetic test case which only exercises xsgetn.

	Base compiler without patch	Base compiler with patch
Total no of instructions (valgrind)	1,378,842	1,359,235
basic_streambuf::xsgetn (char*, long)	20,015	0

```
struct test : public std::basic_streambuf<char> {

  typedef std::basic_streambuf<char> base;

  test() {}

  void setg(char* gbeg, char* gnext, char* gend) {
      base::setg(gbeg, gnext, gend);
  }
};
```

```
int foo(char* input, char *output, int N) {
    test t;

    t.setg(input, input, input+N);
    char* pos = output;
    pos += t.sgetn(pos, N);

    return *pos;
}
```

Suboptimal string::find algorithm (uses std::find)

```
b1, e1 iterators to the haystack string
b2, e2 iterators to the needle string
__search(b1, e1, b2, e2) {
...
while (true)
    {
        while (true)
        {
            if (__first1 == __s)
                return make_pair(__last1, __last1);
            if (__pred(*__first1, *__first2))
                break;
            ++__first1;
        }

        _RandomAccessIterator1 __m1 = __first1;
        _RandomAccessIterator2 __m2 = __first2;
         while (true)
         {
             if (++__m2 == __last2)
                 return make_pair(__first1, __first1 + __len2);
             ++__m1;
             if (!__pred(*__m1, *__m2))
             {
                 ++__first1;
                 break;
             }
         }
    }
}
...
}
```

Find the first matching character

Match rest of the string

Optimized string::find algorithm

```
inline _LIBCPP_CONSTEXPR_AFTER_CXX11 const _CharT *
__search_substring(const _CharT *__first1, const _CharT *__last1, const _CharT *__first2, const _CharT *__last2) {
…
  // First element of __first2 is loop invariant.
  _CharT __f2 = *__first2;
  while (true) {
    __len1 = __last1 - __first1;
    // Check whether __first1 still has at least __len2 bytes.
    if (__len1 < __len2)
      return __last1;

    // Find __f2 the first byte matching in __first1.
    __first1 = _Traits::find(__first1, __len1 - __len2 + 1, __f2);
    if (__first1 == 0)
      return __last1;
```

Find the first matching character

```
    if (_Traits::compare(__first1, __first2, __len2) == 0)
      return __first1;
```

Match rest of the string

```
    ++__first1; // TODO: Boyer-Moore can be used.
  }
}
```

Performance improvements

Benchmark	Without patch	With patch	Gain
BM_StringFindMatch1/32768	28157 ns	2203 ns	12.8x
BM_StringFindMatch2/32768	28161 ns	2204 ns	12.8x

```
// Match somewhere towards the end
static void
BM_StringFindMatch1(benchmark::State &state)
{
  std::string s1(MAX_STRING_LEN / 2, '*');
  s1 += std::string(state.range(0), '-');

  std::string s2(state.range(0), '-');

  while (state.KeepRunning())
    benchmark::DoNotOptimize(s1.find(s2));
}
```

```
// Match somewhere from middle to the end.
static void
BM_StringFindMatch2(benchmark::State &state)
{
  std::string s1(MAX_STRING_LEN / 2, '*');
  s1 += std::string(state.range(0), '-');
  s1 += std::string(state.range(0), '*');

  std::string s2(state.range(0), '-');

  while (state.KeepRunning())
    benchmark::DoNotOptimize(s1.find(s2));
}
```

Missing inlining opportunities in basic_string (libc++)

- Important functions not inlined.
  - basic_string::__init(const value_type* __s, size_type __sz)
  - basic_string::~basic_string()
- Clang front end does not emit the definition of these functions (extern templates) in the IR
- Solution
  - Mark functions as inline

Missing function attributes (libc++)

- Missing __attribute__((__noreturn__)) in important functions.
  - Prevents important compiler optimizations
  - Results in false positives in static analysis results
- __throw.* functions in __locale, deque, future, regex, system_error, vector

Example:

```
class __vector_base_common {
protected:
  __vector_base_common() {}
  void __throw_length_error() const;
  void __throw_out_of_range() const;
};
```

Issues with number parsing in locale (libc++)

- Uses std::string to store the parsed numbers
  - Results in (unnecessary) calls to memset
- Possible characters for all kinds of numbers (octal, hex, decimal) are stored in one string
  - __atoms = “0123456789abcdefABCDEFxX+-pPiInN”
- Makes unnecessary copies of ‘__atoms’ string which are not modified in common case

Issues with number parsing in locale (libc++)

- Avoiding copy of __atoms is hard because of ABI incompatibilities.
- Current workaround is to version the change with a macro

Benchmark	Without patch	With patch	Gain
BM_Istream_numbers/32	8336 ns	7472 ns	11%

* Benchmark source: std-benchmark/cxx/stringstream.bench.cpp

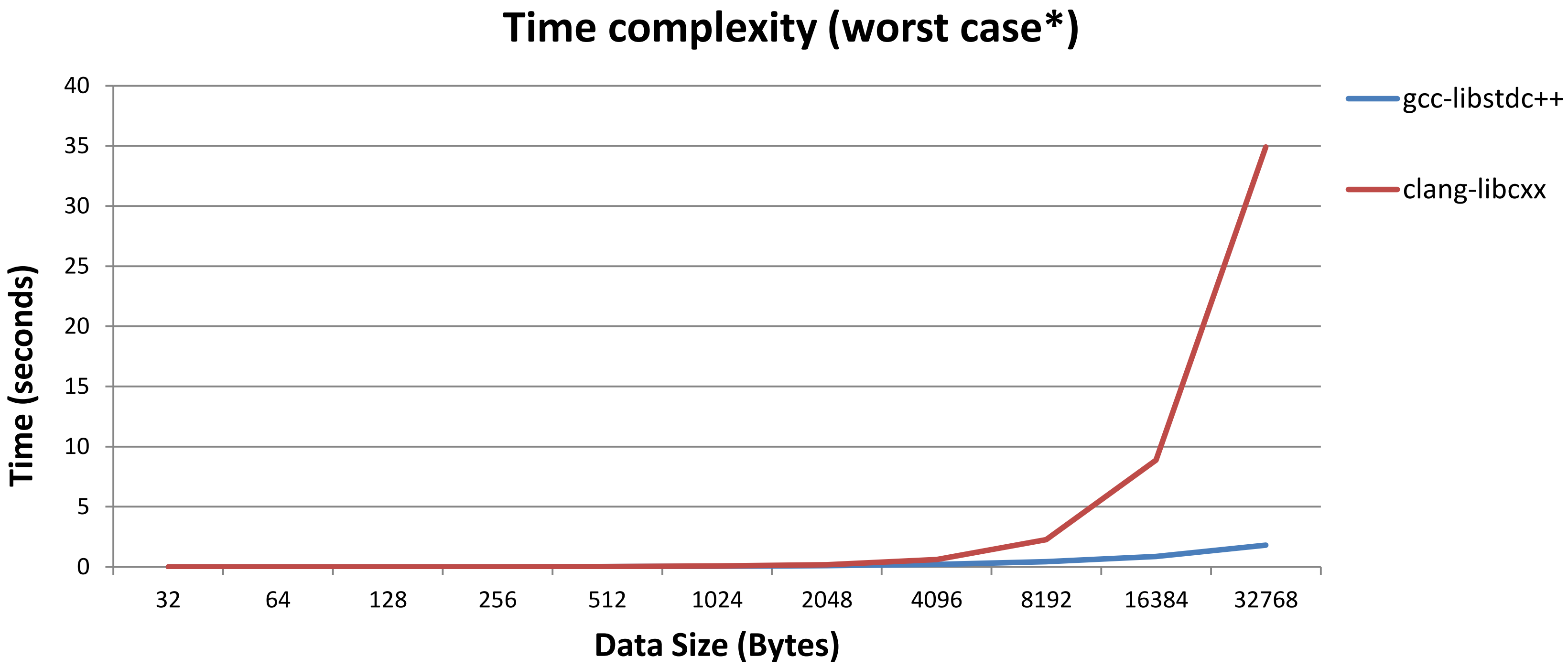
* https://reviews.llvm.org/D30268

std-benchmark

- https://github.com/hiraditya/std-benchmark
  - WIP
  - Builds on Linux, Windows (thanks to cmake)
  - Performance numbers are very stable (based on google-benchmark)

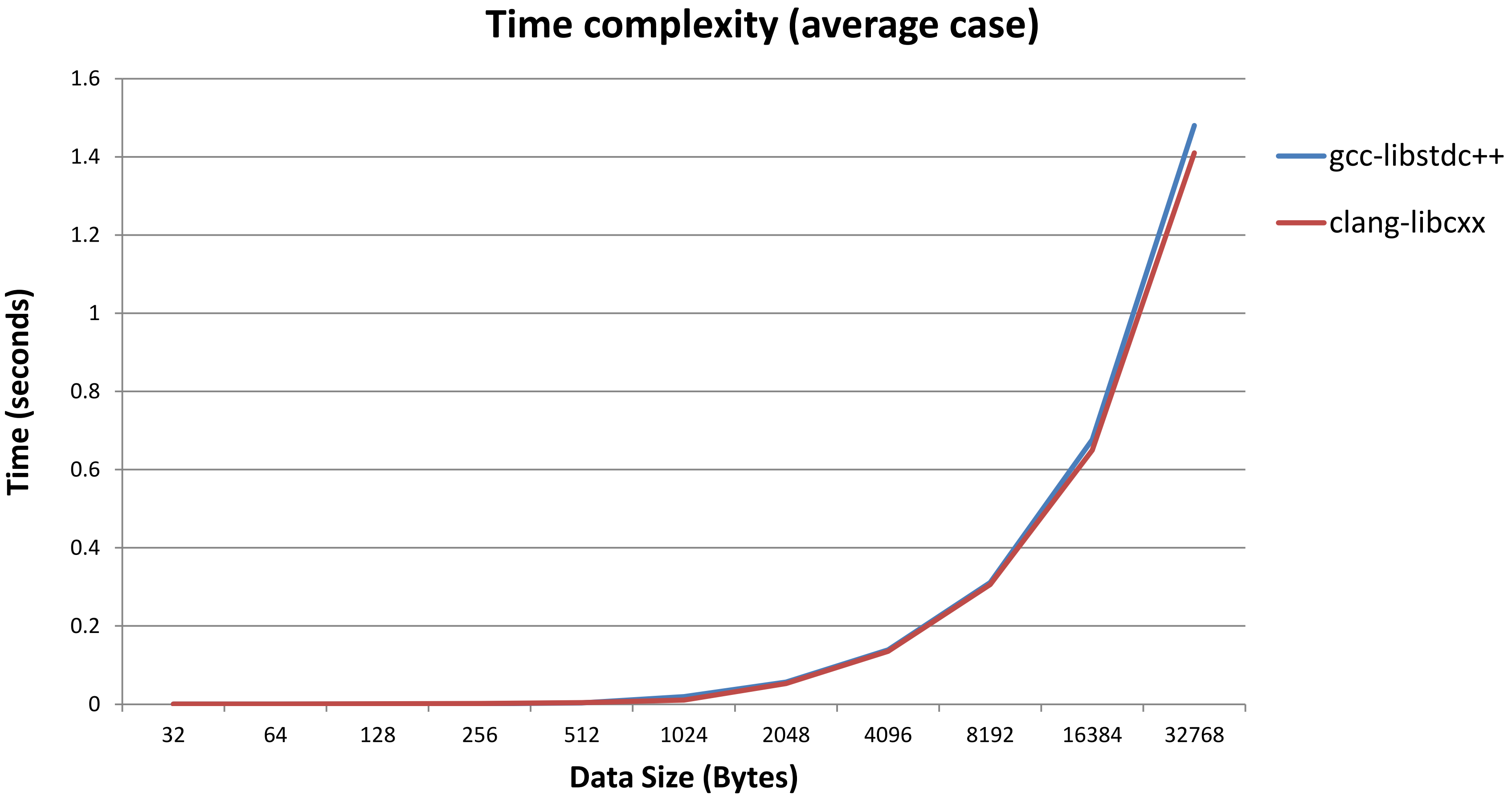
Issues with sort (libc++)

- Worst case
  - clang-libc++ O(N^2) vs. gcc-libstdc++ O(NlogN)

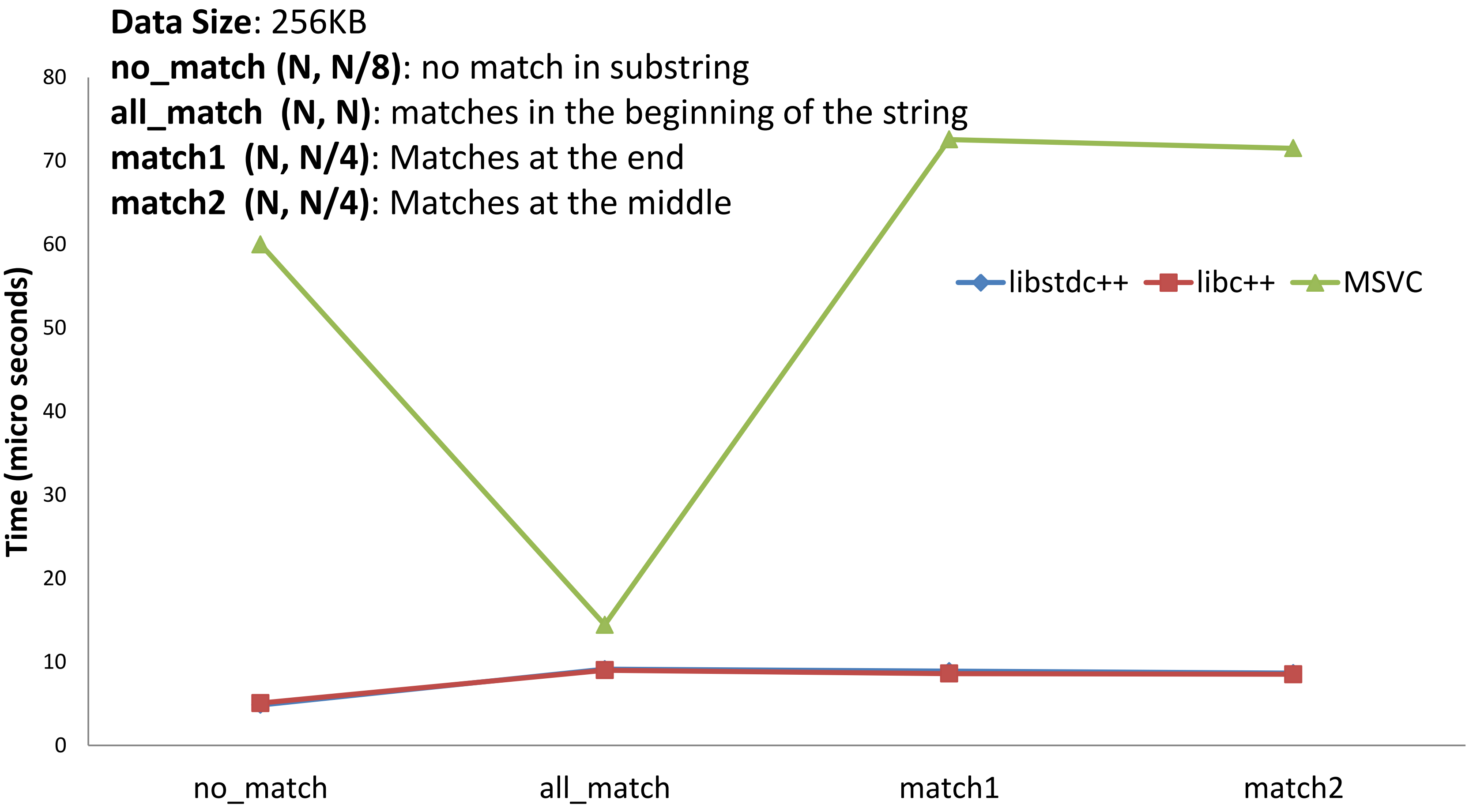


* https://bugs.llvm.org/show_bug.cgi?id=20837

sort (Average case)



string::find



Data Size: 256KB

no_match (N, N/8): no match in substring

all_match (N, N): matches in the beginning of the string

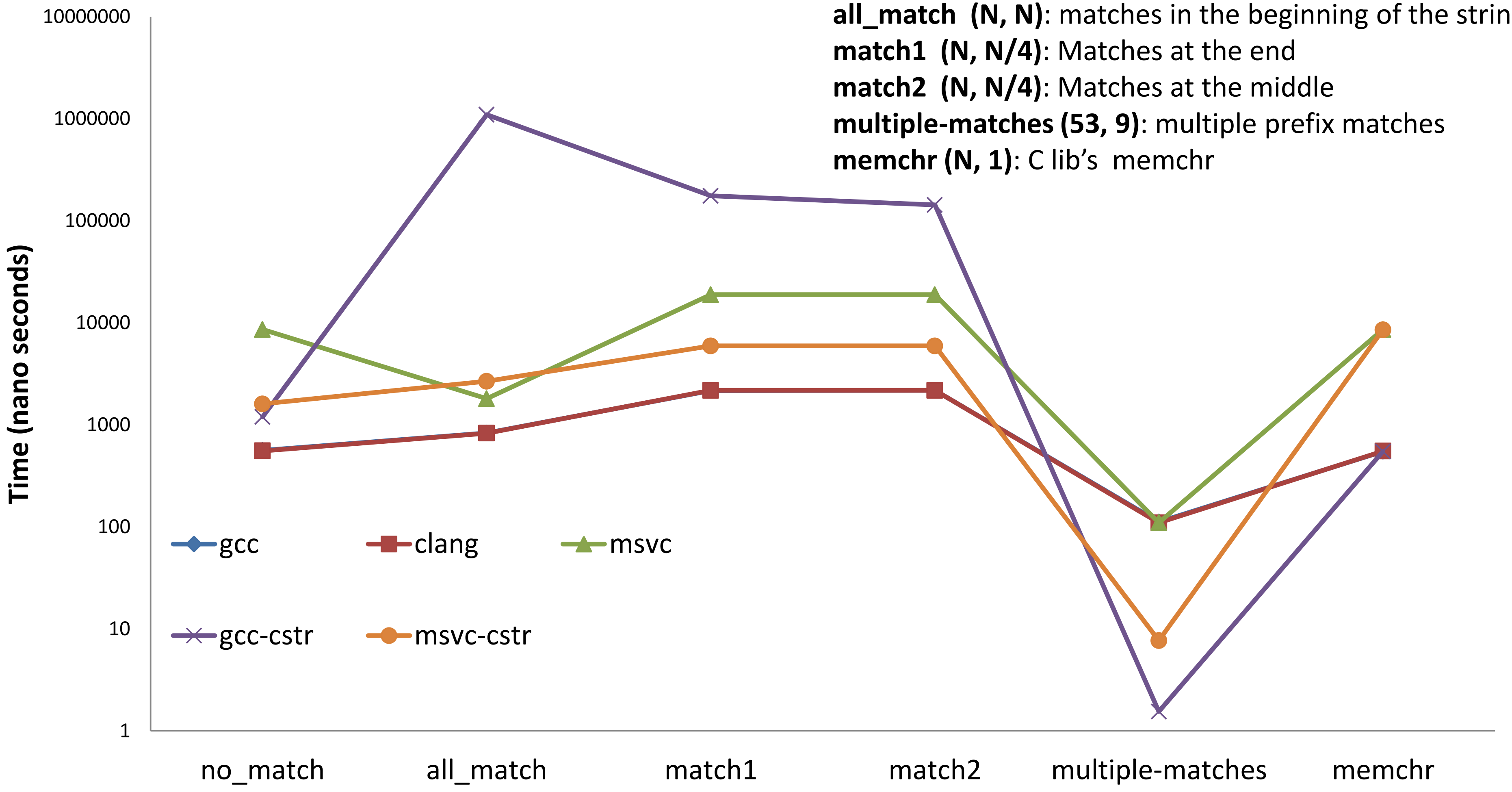
match1 (N, N/4): Matches at the end

match2 (N, N/4): Matches at the middle

* Lower is better.

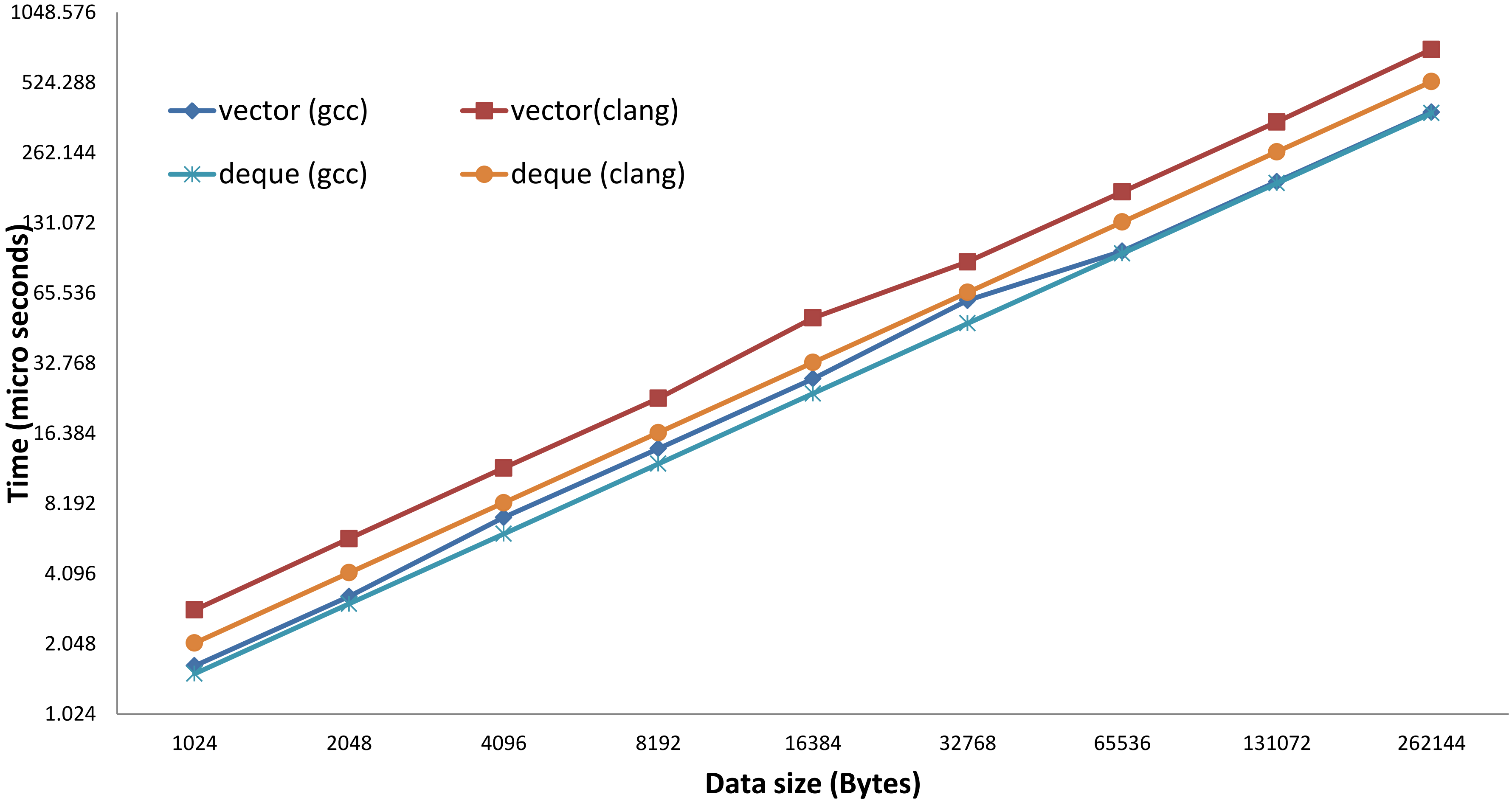
string::find vs. strstr

Data size: 32 KB
no_match (N, N/8): no match in substring
all_match (N, N): matches in the beginning of the string
match1 (N, N/4): Matches at the end
match2 (N, N/4): Matches at the middle
multiple-matches (53, 9): multiple prefix matches
memchr (N, 1): C lib's memchr



* Lower is better.

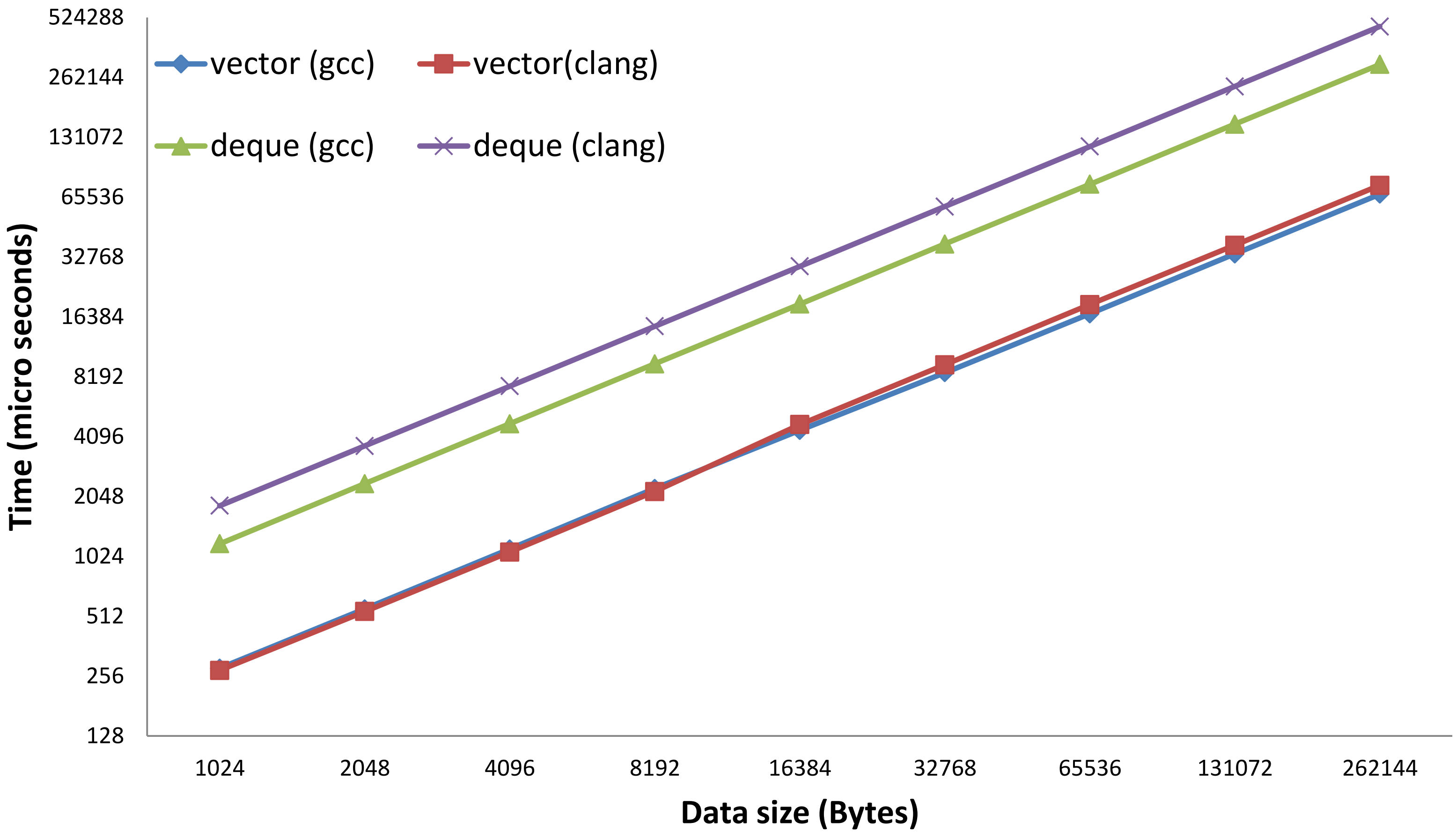
vector vs. deque (push_back)



* [push_back N elements]

* Lower is better.

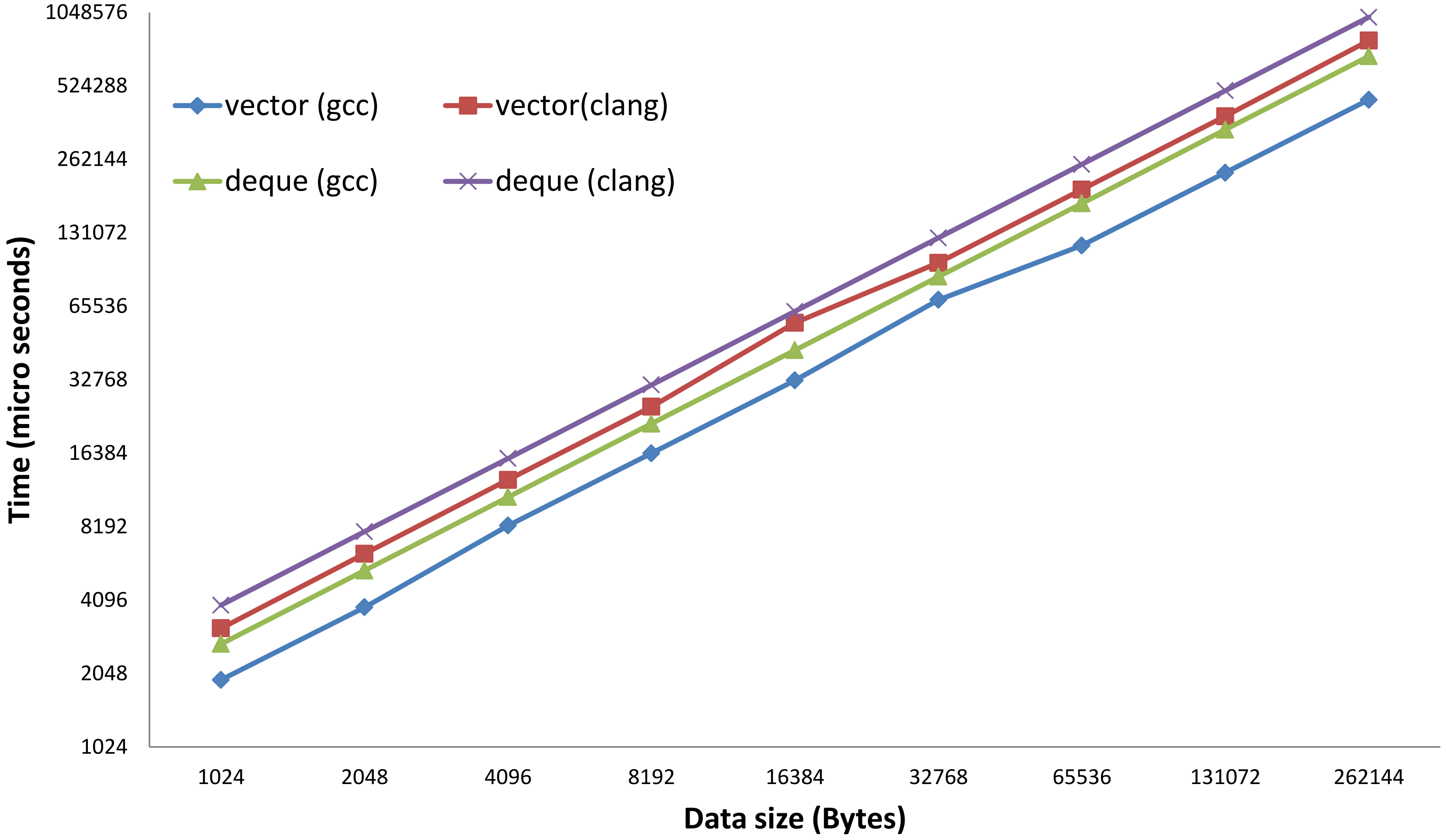
vector vs. deque (access)



* [access N elements in sequence]

* Lower is better.

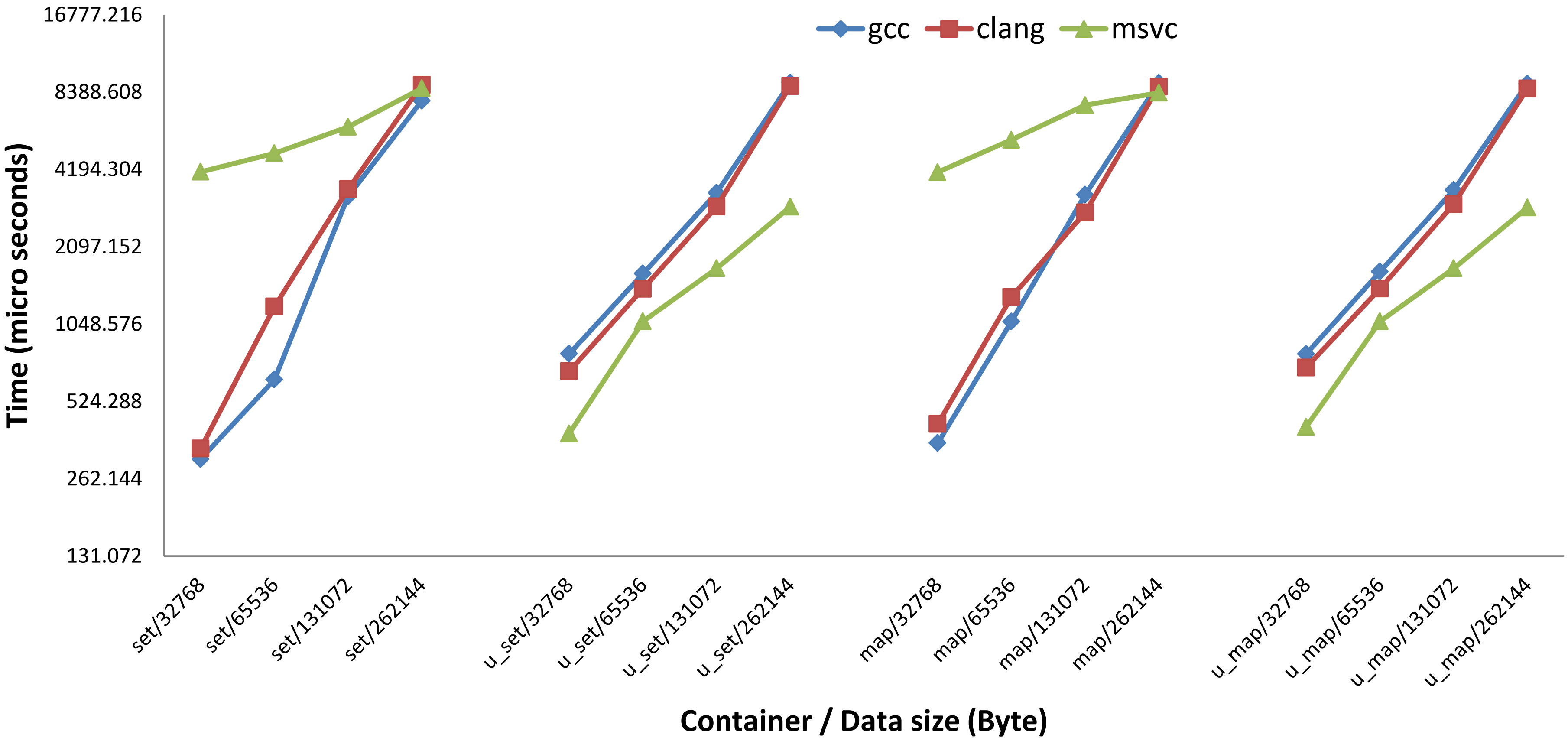
vector vs. deque (push_back + access)



* [push_back N elements + access N elements in sequence]

* Lower is better.

Associative vs Hashed Associative (Finding random integers)



* Lower is better.

compiler vs. programmer vs. hand-optimized

Relative performance w.r.t. g++ (Lower is better)			
Data: 32KB	programmer	compiler	C-memcpy
MSVC	11	11	1.04
clang++	1	1	1.3
g++	1	1.3	1.3

```
// Programmer
const char*
assign(const char *beg,
          const char *end, char *dest)
{
  while (beg != end)
    *dest++ = *beg++;
  return beg;
}
```

```
// Compiler
const char*
assign_res(const char * __restrict beg,
                   const char * __restrict end,
                   char *__restrict dest)
{
  while (beg != end)
    *dest++ = *beg++;
  return beg;
}
```

Lessons learned (Algorithms)

- rotate but not std::rotate on linked lists
- std::find may not always be the right choice

Lessons learned (containers)

- Consider total cost
  - Take ratio of reads/writes to decide
  - vector causes memory fragmentation (~2N allocations for N elements)
  - if reads < writes, deque can be a better choice
- ‘resize’ initializes the memory

Lessons learned (containers)

- string
  - calls memset when resized
  - destructor is difficult to optimize away

Lessons learned (containers) optimizing destructor of string

```
#include<string>

int main() {
  std::string s("a");
  s+='a';
  return 0;
}
```

```
$ g++ -O3 t.cpp -S –fno-exceptions –std=c++11 -o - | grep _ZdlPv

$ clang++ -O3 t.cpp -S –fno-exceptions –std=c++11 -o - | grep _ZdlPv
        call    _ZdlPv
```

```
#include<string>
void foo();

int main() {
  const std::string s("a");
  foo();
  return 0;
}
```

```
$ g++ -O3 t.cpp -S –fno-exceptions –std=c++11 -o - | grep _ZdlPv
        call    _ZdlPv

$ clang++ -O3 t.cpp -S –fno-exceptions –std=c++11 -o - | grep _ZdlPv
```

Lessons learned (Language/Library)

- The constructor and destructor cannot be const qualified*
- Iterator based algorithms can lose information and hence, can result in suboptimal performance
- No optimized algorithms for non-char arrays
- Using unsigned int as induction variable is okay
  - With recent gcc (gcc.gnu.org/PR48052)

(*) Kevlin Henney: http://www.open-std.org/jtc1/sc22/wg21/docs/papers/1995/N0798.htm

Size (in bytes) of empty containers
64 bit

Container	libstdc++	libc++	MSVC
vector<int>	24	24	24
list<int>	24	24	16
deque<int>	80	48	40
set<int>	48	24	16
unordered_set<int>	56	40	64
map<int, int>	48	24	16
unordered_map<int, int>	56	40	64

Optimize for latency

Memory	Latency (cycles)
L1	4
L2	12
L3	36
RAM	36+57ns

Intel i7-4770 3.4GHz (Turbo Boost off) 22 nm. RAM: 32 GB (PC3-12800 cl11 cr2).

Source: http://www.7-cpu.com/cpu/Haswell.html

References

- https://gcc.gnu.org/onlinedocs/libstdc++/index.html
- http://clang-analyzer.llvm.org/annotations.html#attr_noreturn
- https://reviews.llvm.org/D21103
- https://reviews.llvm.org/D22782
- https://reviews.llvm.org/D22834
- https://reviews.llvm.org/D21232
- https://reviews.llvm.org/D27068
- https://github.com/google/benchmark
- https://github.com/hiraditya/std-benchmark