Performance analysis and optimization

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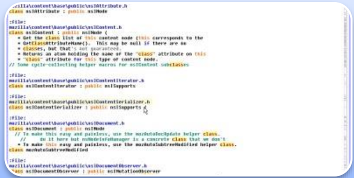
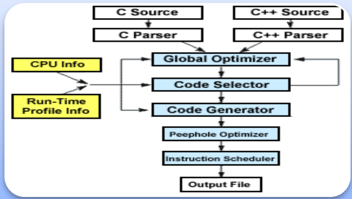
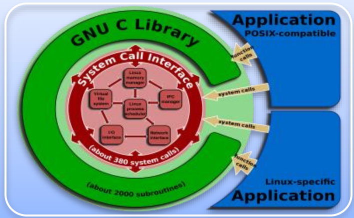
System Performance



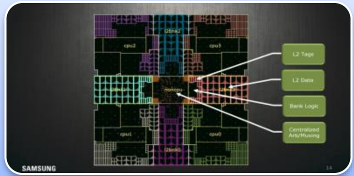
Code:



Compiler: GCC, LLVM, ICC, MSVC



RT-libs and system: libstdc++, glibc, libgcc, compiler-rt



Hardware: AArch64, Intel, RISC-V

Ways to improve performance

Improve runtime of algorithms
- Removing recursion, redundancies
- Micro optimizations tend to become less relevant with new compilers/runtime/hardware

Change algorithms
- Bubble sort to quick sort

Using right data structures
- list to vector, map to hash_map
- Encoding data intelligently

Switching to recent compiler versions
- GCC 12

Using improved language features, or optimize existing language semantics
- C++17/20 (RVO, compile time evaluations, noexcept)

Changing the programming language
- Java to C++
- Customizing the compiler to modify semantics of the language within certain constraints

Profile based optimization
- Hand optimization, AutoFDO, PGO

Improve runtime of algorithms

Suboptimal basic_streambuf::xsgetn (libc++)

```
template <class _CharT, class _Traits>
streamsize
xsgetn(char_type* __s, streamsize __n) {
  streamsize __i = 0;
  for (; __i < __n; ++__i, ++__s) {
    if (__ninp_ < __einp_)
      *__s = *__ninp_++;
    else
      break;
  }
return __i;
}
```

Optimized basic_streambuf::xsgetn

```
// Before

template <class _CharT, class _Traits>
streamsize
xsgetn(char_type* __s, streamsize __n) {
  streamsize __i = 0;
  for (; __i < __n; ++__i, ++__s) {
    if (__ninp_ < __einp_)
      *__s = *__ninp_++;
    else
      break;
  }
return __i;
}
```

```
// After

template <class _CharT, class _Traits>
streamsize xsgetn(char_type* __s, streamsize __n)
{
  streamsize __i = 0;
  while (__i < __n) {
    if (__ninp_ < __einp_) {
      const streamsize __len = std::min(__einp_ - __ninp_, __n - __i);
      traits_type::copy(__s, __ninp_, __len);
      __s += __len;
      __i += __len;
      this->gbump(__len);
    }
    else
      break;
  }
return __i;
}
```

Suboptimal string::find algorithm

```
// 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;
      }
    } // End While

  } // End While

}
```

Find the first matching character

Match rest of the string

Optimized string::find algorithm

```
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;

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

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

}
```

Find the first matching character

Match rest of the string

Performance improvements

Benchmark	Without patch	With patch	Gain
Test1/32768	28157 ns	2203 ns	12.8x
Test2/32768	28161 ns	2204 ns	12.8x

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()

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() {}
__attribute__((__noreturn__))  void __throw_length_error() const;
__attribute__((__noreturn__))  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) stored in one string

- __atoms = “0123456789abcdefABCDEFxX+-pPiInN”

Makes unnecessary copies of ‘__atoms’ string which are not modified in common case

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;
}
```

```
// Helping compiler with user annotation
const char*
assign_res(const char * __restrict beg,
           const char * __restrict end,
           char *__restrict dest)
{
  while (beg != end)
    *dest++ = *beg++;
  return beg;
}
```

Change algorithms

Bernstein Hash

```
uint32_t ComputeHash(const ZipString& name)
{
  uint32_t hash = 0;
  uint16_t len = name.name_length;
  const uint8_t* str = name.name;
  while (len--) {
    hash = hash * 31 + *str++;
  }
  return hash;
}
```

Improved Bernstein Hash

```
// After
uint32_t ComputeHash(const ZipString& name)
{
  uint32_t hash = 0;
  uint16_t len = name.name_length;
  const uint8_t* str = name.name;
  unsigned chunk;
  const unsigned sz = sizeof(chunk);

  // Hash sz bytes at a time.
  while (len > sz) {
    // Why not plain typecast??
    __builtin_memcpy(&chunk, str, sz);
    hash = hash * 31 + chunk;
    len -= sz;
    str += sz;
  }

  // Hash the left-over bytes.
  while (len--) {
    hash = hash * 31 + *str++;
  }
  return hash;
}
```

```
// Before
uint32_t ComputeHash(const ZipString& name)
{
  uint32_t hash = 0;
  uint16_t len = name.name_length;
  const uint8_t* str = name.name;
  while (len--) {
    hash = hash * 31 + *str++;
  }
  return hash;
}
```

Comment: standard library algorithms

Iterator based algorithms can lose information and hence, can result in suboptimal performance

- std::rotate on doubly linked list. Same algorithms can be writtren optimally for ranges

No optimized algorithms for non-char arrays

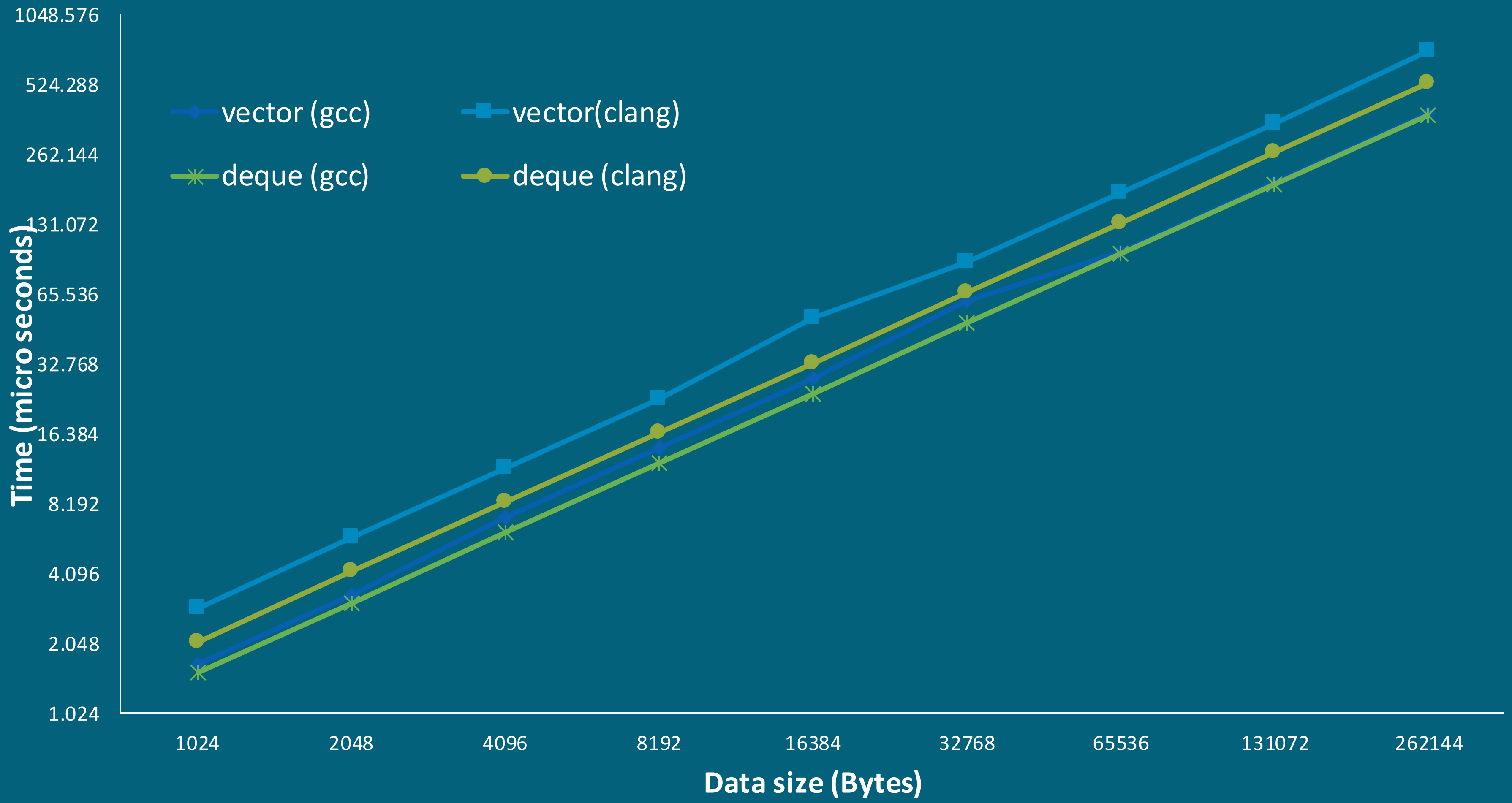
- Copying an array of pairs

std::find may not always be the right choice

- substr

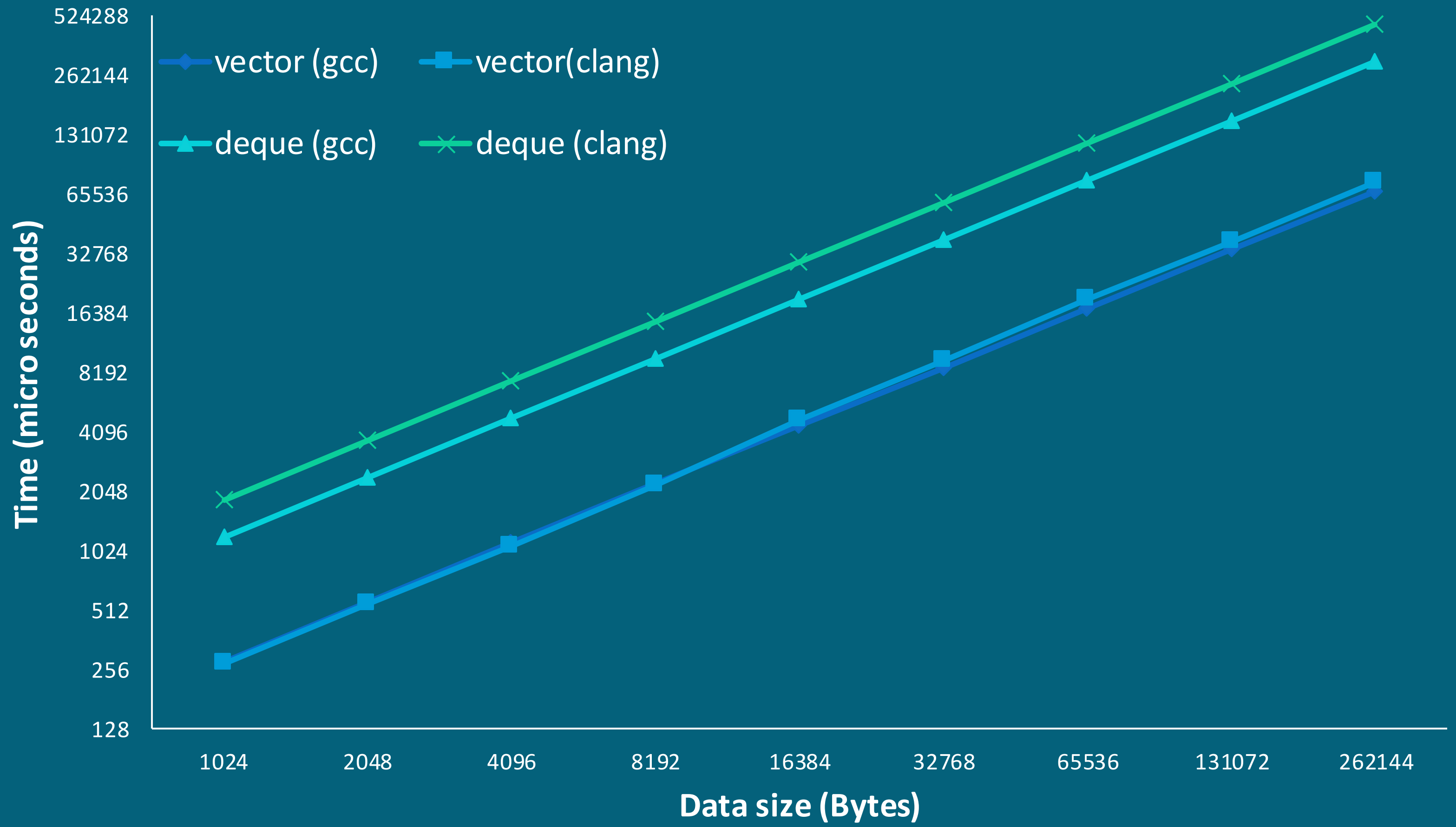
Changing the data structure

vector vs. deque (push_back)



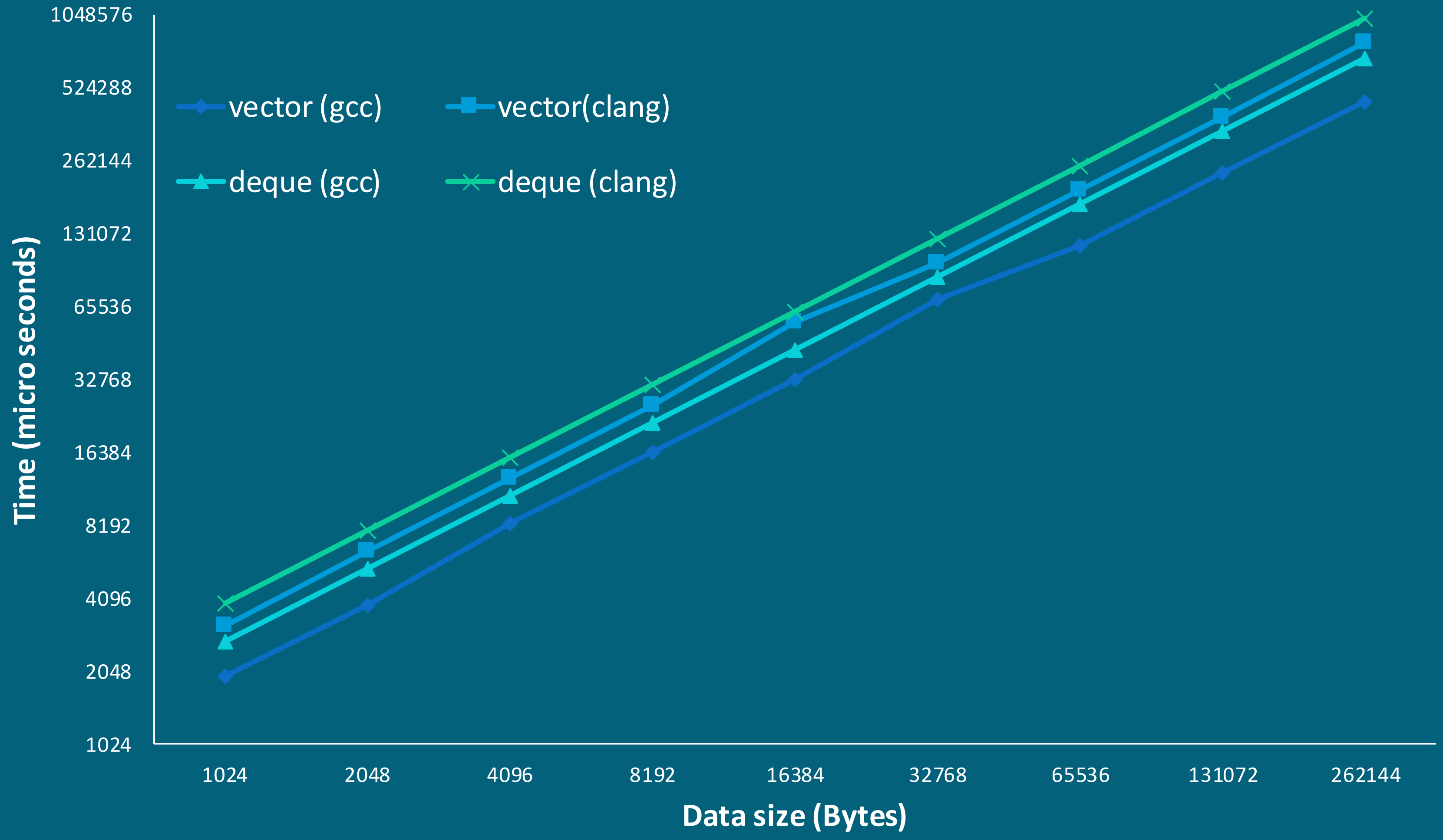
* [push_back N elements]
* Lower is better.

vector vs. deque (access)



* [access N elements in sequence]
* Lower is better.

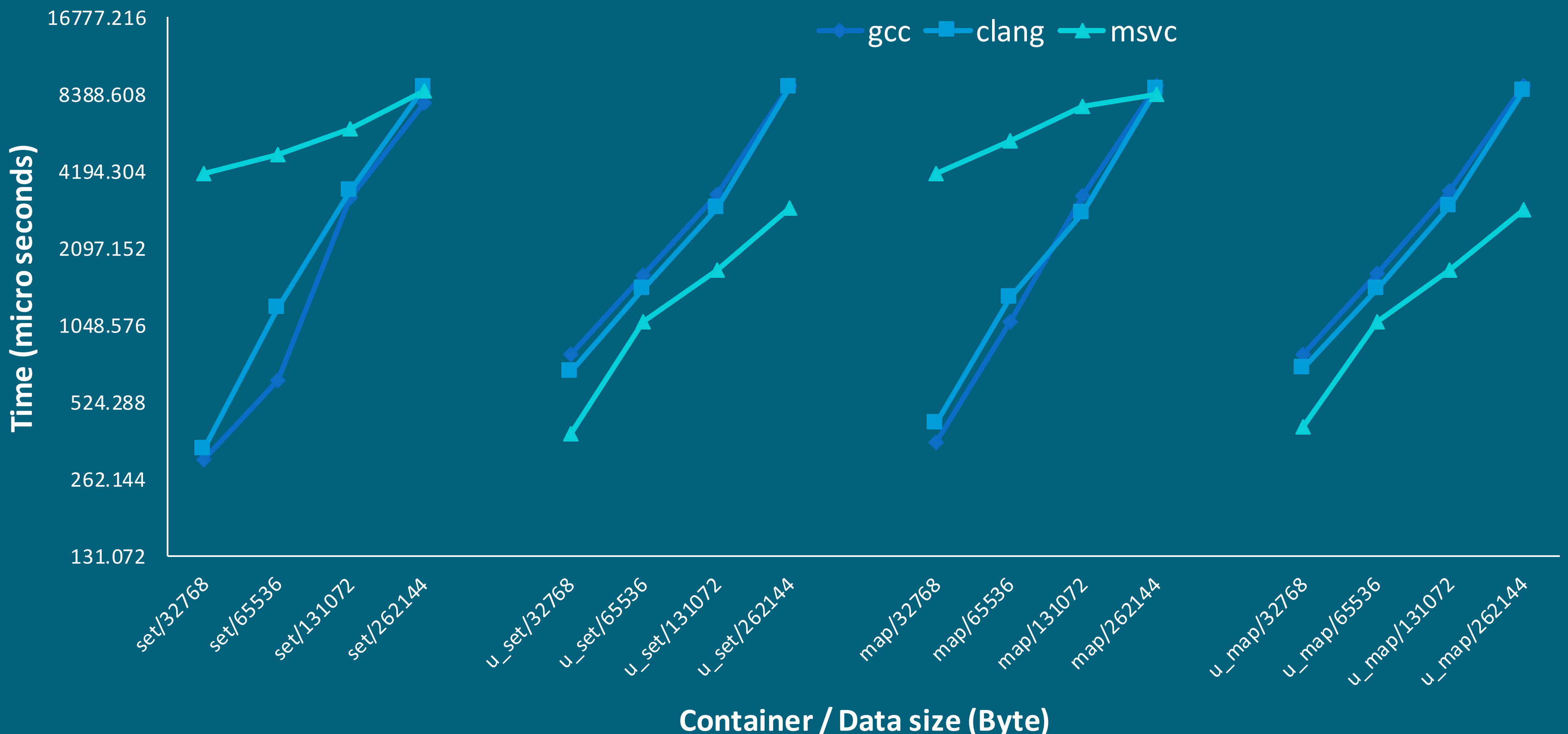
vector vs. deque (push_back + access)



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

* Lower is better

Associative vs Hashed Associative (Finding random integers)



* Lower is better

Comment: standard library 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

Encoding data intelligently

Find two numbers such that sum is zero

```
#include<algorithm>
#include<array>
#include<iostream>

template<typename T>
// Returns the positions in [b, e) which sum to zero.
std::pair<T, T> find_complement(T b, T e) {
 T p1 = b;
 T p2 = e;
 --p2; // Point to the last element of the range.
 while (p1 != p2) {
   int sum = *p1 + *p2;
   if (sum == 0)
     return {p1, p2}; // Preserve the information computed
   else if (sum < 0)
     ++p1;
   else // sum > 0
     --p2;
 }
 return {nullptr, nullptr};
}

int main() {
 std::array<int, 9> a{ -4, -4, -1, 0, 1, 2, 3, 4, 4 };
 std::pair<int*, int*> v = find_complement(a.begin(), a.end());
 if (v.first != nullptr) {
   std::cout << "\nFound: " << *v.first << ", " << *v.second;
 }
 return 0;
}
```

Encoding data intelligently

Find all pairs such that sum is zero

```
#include<algorithm>
#include<array>
#include<iostream>

template<typename T>
// Returns the positions in [b, e) which sum to zero.
std::pair<T, T> find_complement(T b, T e) {
 T p1 = b;
 T p2 = e;
 --p2; // Point to the last element of the range.
 while (p1 != p2) {
   int sum = *p1 + *p2;
   if (sum == 0)
     return {p1, p2}; // Preserve the information computed
   else if (sum < 0)
     ++p1;
   else // sum > 0
     --p2;
 }
 return {nullptr, nullptr};
}

int main() {
 std::array<int, 9> a{ -4, -4, -1, 0, 1, 2, 3, 4, 4 };
 std::pair<int*, int*> v = find_complement(a.begin(), a.end());
 while (v.first != nullptr) {
   std::cout << "\nFound: " << *v.first << ", " << *v.second;
   v = find_complement(++v.first, v.second);
 }
 return 0;
}
```

Switching to new compiler/language versions

```cpp
#include<string>

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

```
$ g++ -O3 t.cpp -S –fno-exceptions –std=c++20 -o - | grep _ZdlPv
        # Optimized away!
$ clang++ -O3 t.cpp -S –fno-exceptions –std=c++20 -o - | grep _ZdlPv
        # Optimized away!
```

```cpp
#include<string>

void foo();

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

```
$ g++ -O3 t.cpp -S –fno-exceptions –std=c++20 -o - | grep _ZdlPv
        call    _ZdlPvm

$ clang++ -O3 t.cpp -S –fno-exceptions –std=c++20 -o - | grep _ZdlPv
        call    _ZdlPv@PLT
```

https://godbolt.org/z/9o1co74Kz

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

Performance analysis tools

- Valgrind
- Linux Perf
- Visual studio performance tools
- Intel Vtune
- XCode Instruments

Performance Analysis with Valgrind

valgrind [--tool=memcheck]

- valgrind mostly known for its memory leak checker

valgrind --tool=cachegrind

- cache and branch simulator
- count read, write, and branch instructions

valgrind --tool=callgrind

- execution call graph
- visualization tool kcachegrind

Valgrind: Example – SQLite

```
$ valgrind --tool=cachegrind ./sqlite_llvm <test.sql >/dev/null
[...]
--------------------------------------------------------------------------------
           Ir        I1mr    ILmr            Dr        D1mr      DLmr            Dw        D1mw     DLmw
--------------------------------------------------------------------------------
1,278,771,731 29,231,219 35,783 359,414,267 6,707,514 528,920 197,515,528 2,594,262 171,968  PROGRAM TOTALS


--------------------------------------------------------------------------------
         Ir       I1mr  ILmr          Dr       D1mr     DLmr          Dw     D1mw    DLmw  file:function
--------------------------------------------------------------------------------
363,052,233 7,560,087 3,122 97,707,865 1,084,529  77,197 44,505,055 217,826 29,838  src/sqlite3.c:sqlite3VdbeExec
 95,048,357    80,721   111 33,248,107    59,086   7,273 20,173,275      91      7  src/sqlite3.c:vdbeRecordCompareWithSkip
 68,045,026   695,509 1,144 14,883,933   114,698   1,918  5,525,733 272,507 19,249  src/sqlite3.c:balance
 56,713,554 1,101,002   276 18,416,705   683,914  21,085  3,453,665   1,947     25  src/sqlite3.c:sqlite3BtreeMovetoUnpacked
 45,344,891    59,660    66 13,589,490    66,121  18,775 12,795,281  59,451     86  src/sqlite3.c:sqlite3VdbeRecordUnpack
 36,550,248    47,192    94  9,615,816   217,845  11,567          0       0      0  src/sqlite3.c:cellSizePtr
 35,156,491 1,031,905   859  7,810,853   489,509   1,936  6,546,085 175,469 26,159  /build/glibc-2.19/malloc/malloc.c:_int_malloc
 34,402,967   219,015    40 12,316,213    31,625   1,007          0       0      0  src/sqlite3.c:vdbeRecordCompareInt
```

Perf stat: Example – SQLite

```
$ perf stat ./sqlite_llvm <test.sql >/dev/null

Performance counter stats for './sqlite_llvm':

     1045.856070      task-clock (msec)         #    1.000 CPUs utilized
               1      context-switches          #    0.001 K/sec
               0      cpu-migrations            #    0.000 K/sec
             809      page-faults               #    0.774 K/sec
   1,636,720,010      cycles                    #    1.565 GHz                    [83.16%]
     548,530,227      stalled-cycles-frontend   #   33.51% frontend cycles idle   [83.16%]
     218,991,051      stalled-cycles-backend    #   13.38% backend  cycles idle   [67.04%]
   3,385,841,295      instructions              #    2.07  insns per cycle
                                                #    0.16  stalled cycles per insn [83.54%]
     709,436,490      branches                  #  678.331 M/sec                  [83.54%]
       2,586,354      branch-misses             #    0.36% of all branches        [83.17%]

     1.045918998 seconds time elapsed
```

Perf record: Example – xalancbmk

```
$ perf record ./xalancbmk
$ perf report
   0.20 629a84:   ldr    w9, [x0,#24]
  18.71 629a88:   ldr    w8, [x1,#24]
  12.93 629a8c:   cmp    w9, w8
   2.74 629a90:   b.ne   629af8 <xalanc_1_8::XalanDOMString::equals
   2.00 629a94:   ldp    x8, x10, [x0]
   2.43 629a98:   cmp    x8, x10
   1.80 629a9c:   ldp    x10, x12, [x1]
   1.03 629aa0:   adrp   x11, 704000 <vtable for xalanc_1_8::ReusableArenaBlock+0x8>
   0.53 629aa4:   add    x11, x11, #0xb08
   0.03 629aa8:   csel   x8, x11, x8, eq
   1.33 629aac:   cmp    x10, x12
   0.34 629ab0:   csel   x10, x11, x10, eq
   1.78 629ab4:   cbz    w9, 629b00 <xalanc_1_8::XalanDOMString::equals
   0.02 629ab8:   ldrh   w11, [x8]
   4.02 629abc:   ldrh   w12, [x10]
   3.75 629ac0:   cmp    w11, w12
   1.03 629ac4:   b.ne   629b08 <xalanc_1_8::XalanDOMString::equals
   1.16 629ac8:   lsl    x9, x9, #1
```

AutoFDO: Feedback Directed Optimization

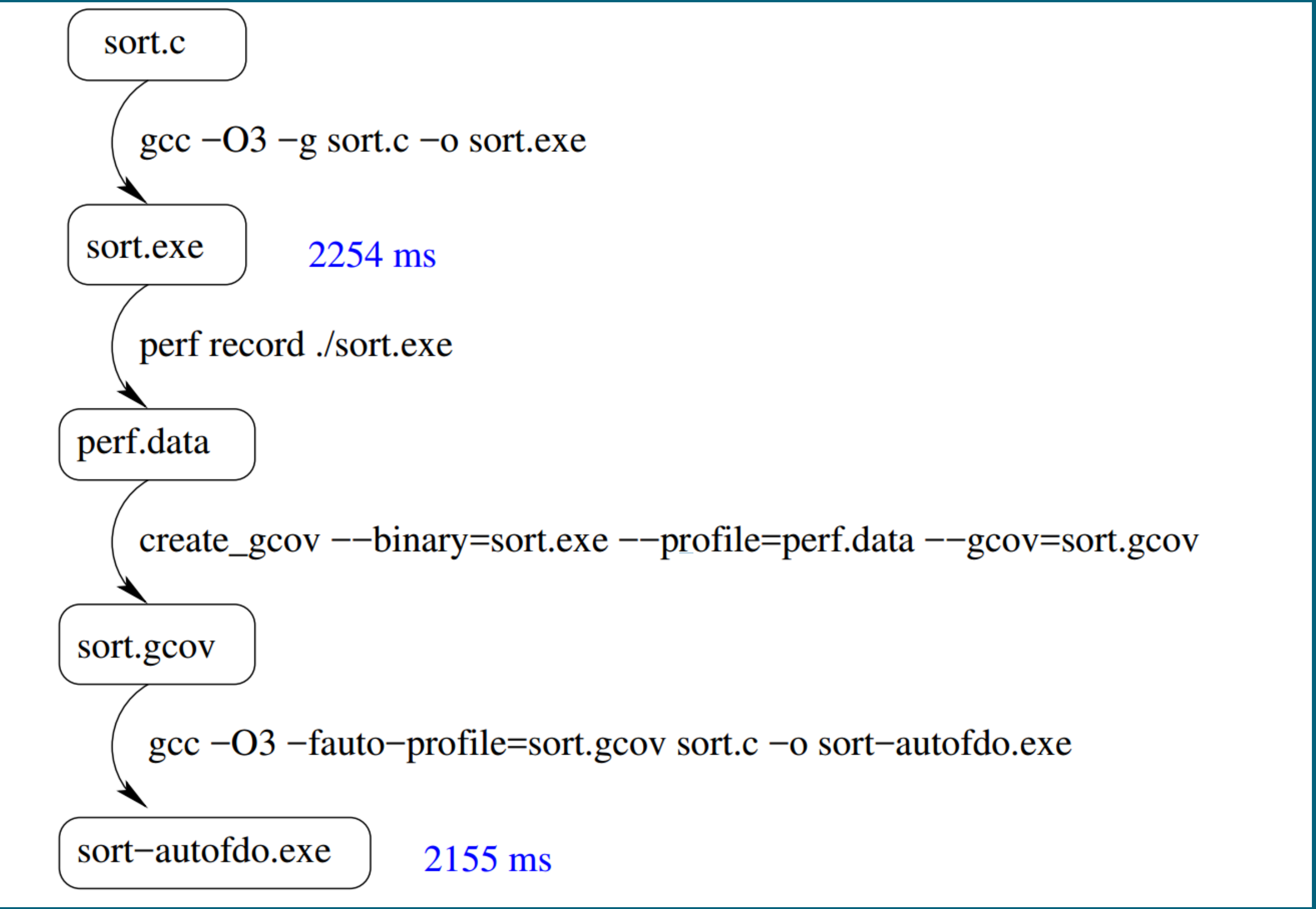
Linux-perf extracts profiles of running systems

little overhead

coverage (basic block frequencies) from dynamic profiles

continuous profiling and tuning of optimizations

AutoFDO: Example



Analyzing System Performance

Vary one Component of the System at a time

- Measure impact of one component on the System
- Run multiple times

Disable frequency scaling

- cpufrequtils

Performance metrics

- Dynamic profiles, compiler logs

Systematic performance analysis

- Monitor performance regression over time
- Time series: track performance of system over time
- Git bisect performance changes

Performance analysis pitfalls

- Central tendency: the median instead of the mean
- Use the quantile values instead of a single median value.
- Outlier detection
- Weighted samples for combining historical data

Performance analysis pitfalls

Central tendencies

- The median instead of the mean

Use the quantile values instead of a single median value

- Helps with prioritization

Outlier detection

- Filter outliers

Weighted samples for combining historical data

- Recent data more important than the previous data.

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)
- https://github.com/hiraditya/hiraditya/tree/master/_posts
- https://github.com/google/benchmark
- https://github.com/hiraditya/std-benchmark

References and Acknowledgements

Acknowledgements:

- Initial version in collaboration with Sebastian Pop (Samsung Austin R&D Center)

Measurement Pitfalls:

- https://stats.stackexchange.com/a/156787
- https://www.longevitas.co.uk/site/informationmatrix/quantilesandpercentiles.html
- https://aakinshin.net/posts/statistics-for-performance/

- Linux perf: http://www.brendangregg.com/perf.html
- Performance Analysis: https://github.com/AndreyAkinshin/perfolizer
- Microbenchmarking: https://www.bfilipek.com/2016/01/micro-benchmarking-libraries-for-c.html
- C++ benchmark tool: https://github.com/ivafanas/sltbench

AutoFDO Resources

- https://gcc.gnu.org/wiki/AutoFDO/Tutorial
- https://github.com/google/autofdo
- https://gcc.gnu.org/lists.html