Italian C++ Community
JUNE 10 - ROME

Social: @MichaelShah
Web: mshah.io
Courses: courses.mshah.io
YouTube: www.youtube.com/c/MikeShah

Optimization Design Patterns

12:15-13:05, Sat, 10th June 2023

50 minutes | Introductory Audience

Your Tour Guide for Today

by Mike Shah

- Associate Teaching Professor at Northeastern University in Boston, Massachusetts.
  - I teach courses in computer systems, computer graphics, and game engine development.
  - My research in program analysis is related to performance building static/dynamic analysis and software visualization tools.
- I do consulting and technical training on modern C++, DLang, Concurrency, OpenGL, and Vulkan projects
  - (Usually graphics or games related)
- I like teaching, guitar, running, weight training, and anything in computer science under the domain of computer graphics, visualization, concurrency, and parallelism.
- Contact information and more on: www.mshah.io
- More online training at courses.mshah.io

Code for the talk

- Located here: https://github.com/MikeShah/Talks/tree/main/2023/2023_italian_cpp

Abstract

The abstract that you read and enticed you to join me is here!

"Premature optimization is the root of all evil" is a saying credited to Donald Knuth that speaks to many programmers with experience -- now anecdotally I have observed folks overlooking the next sentence stating: "Yet we should not pass up our opportunities in that critical 3%". In this talk, the audience will be introduced to some common optimization design patterns. I will discuss precomputation, lazy versus eager evaluation, batching, caching, specialization, hinting, hashing, and using your compiler among 'optimization design patterns' that every programmer should be aware of. Examples will be demonstrated in Modern C++, and the goal is for the audience to leave feeling comfortable implementing each optimization design pattern to improve performance of their code.

Question to Audience:

How many of you have heard this phrase?
(On the next slide...)

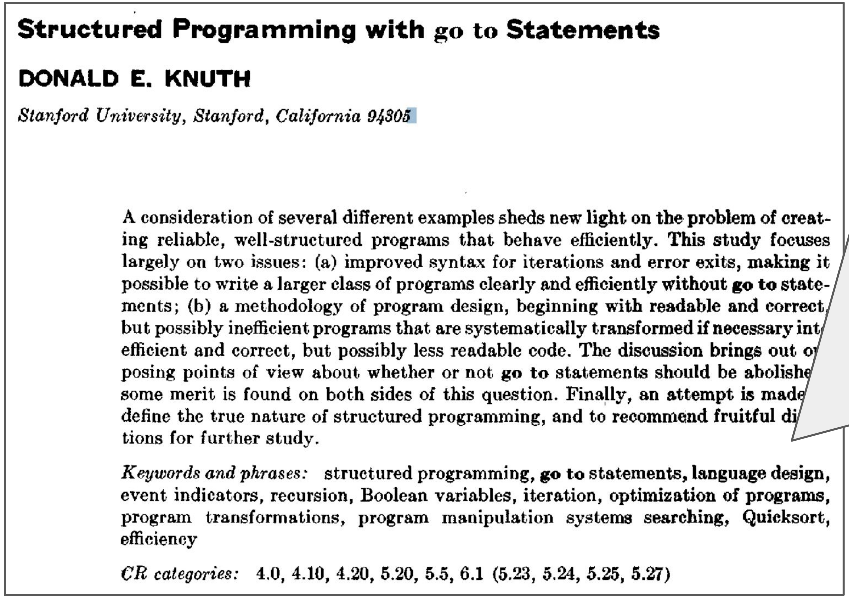
“premature optimization is the root of all evil [or at least most of it in programming].” - Donald Knuth

Question to Audience:

How many of you have read Knuth's Paper in which this is quoted?

Structured Programming with go to Statements (1/3)

- The original paper is filled with lots of gems (including the famous quoted statement)



Structured Programming with go to Statements

DONALD E. KNUTH

Stanford University, Stanford, California 94305

A consideration of several different examples sheds new light on the problem of creating reliable, well-structured programs that behave efficiently. This study focuses largely on two issues: (a) improved syntax for iterations and error exits, making it possible to write a larger class of programs clearly and efficiently without **go to** statements; (b) a methodology of program design, beginning with readable and correct, but possibly inefficient programs that are systematically transformed if necessary int efficient and correct, but possibly less readable code. The discussion brings out o posing points of view about whether or not **go to** statements should be abolishe some merit is found on both sides of this question. Finally, an attempt is made define the true nature of structured programming, and to recommend fruitful di tions for further study.

Keywords and phrases: structured programming, **go to** statements, language design, event indicators, recursion, Boolean variables, iteration, optimization of programs, program transformations, program manipulation systems searching, Quicksort, efficiency

CR categories: 4.0, 4.10, 4.20, 5.20, 5.5, 6.1 (5.23, 5.24, 5.25, 5.27)

Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered. We should forget about small efficiencies, say about 97% of the time: **premature optimization is the root of all evil.** Yet we should not pass up our opportunities in that critical 3 %. A good programmer will not be lulled into complacency by such reasoning, he will be wise to look carefully at the critical code; but only after that code has been identified. It is often a mistake to make a priori judgments about what parts of a program are really critical, since the universal experience of programmers who have been using measurement tools has been that their intuitive guesses fail. After working with such tools for seven years, I've become convinced that all compilers written from now on should be designed to provide all programmers with feedback indicating what parts of their programs are costing the most; indeed, this feedback should be supplied automatically unless it has been specific Mly turned o

Structured Programming with go to Statements (2/3)

- There’s also this one too right after!

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Structured Programming with go to Statements (3/3)

- And where exactly to optimize

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(potentially bad if facing a new challenge)

"premature optimization is the root of all evil" 'But never optimizing when the opportunity is available is also evil'

- This is how I paraphrase Knuth to my students

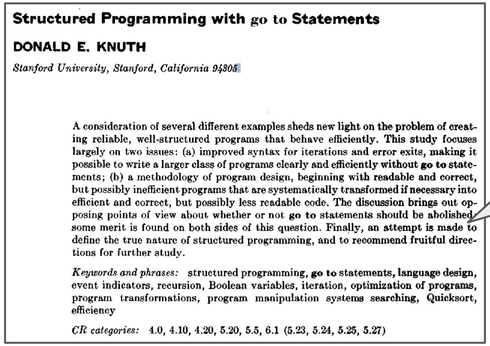
(*Again, Knuth is not saying to never optimize)

Optimization is Tricky

(You’re going to see in my examples!)

More from Knuth [Original Paper link] (1/4)

(From Knuth's paper)



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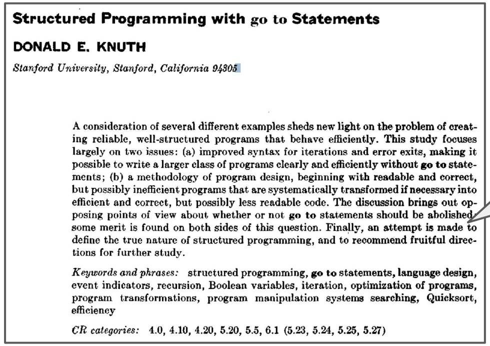
More from Knuth [Original Paper link] (2/4)

- Optimization *might* result in you making trade-offs beyond space and time
  - e.g. readability, maintainability, and sometimes even correctness/precision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More from Knuth [Original Paper link] (3/4)

- However, I might add, sometimes the simplest code is the most optimized!
    - It's easiest for the hardware to predict -- so we really have to know the whole software and hardware stack!

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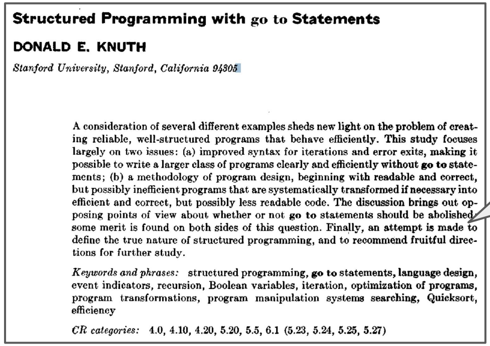

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More from Knuth [Origina

- However, I might add, sometimes the simplest code is the most optimized!
  - It's easiest for the hardware to predict -- so we really have to know the whole software and hardware stack!

- Will some patterns that I demonstrate obfuscate and make your code harder to read?
  - Maybe (though they are simple for today's introduction)
  - But hopefully you'll become familiar with some tools to help you choose the right optimization strategy.

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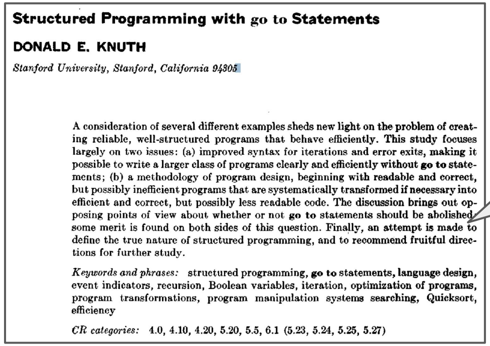

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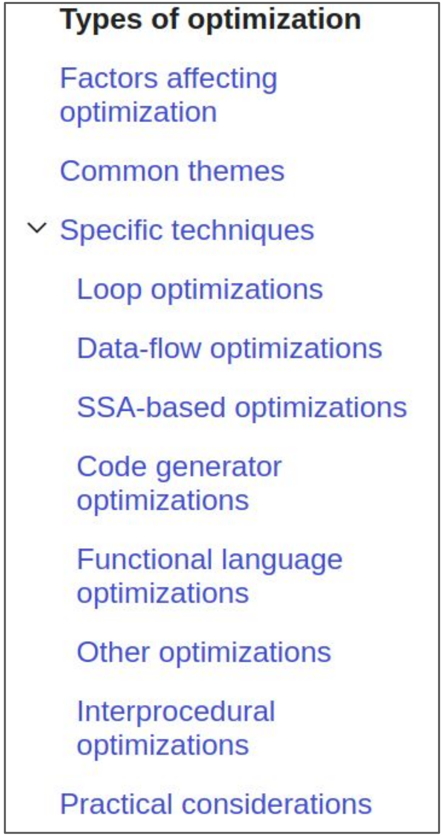
(Aside) CPU, Hard drive, and general Architecture

- This talk is too short to discuss how hardware works -- BUT there are some great talks you could watch to get up to speed and are also performance related
  - code::dive conference 2014 - Scott Meyers: Cpu Caches and Why You Care
    - https://www.youtube.com/watch?v=WDIkqP4JbkE
  - CppCon 2014: Mike Acton "Data-Oriented Design and C++"
    - https://www.youtube.com/watch?v=rX0ItVEVjHc
  - CppCon 2016: Timur Doumler “Want fast C++? Know your hardware!"
    - https://www.youtube.com/watch?v=BP6NxVxDQIs
  - CppCast Episode 287: Trading Systems with Carl Cook
    - https://youtu.be/nmIJqiOtWSs?t=948 (Specifically on the challenges)
  - "Performance Matters" by Emery Berger
    - https://www.youtube.com/watch?v=r-TLSBdHe1A
  - CppCon 2016: Chandler Carruth “High Performance Code 201: Hybrid Data Structures"
    - https://www.youtube.com/watch?v=vElZc6zSIXM

(Aside) Compiler Optimizations

- Compilers aren't really a pattern but a great place to look for 'themes' in how to write fast code.
  - It's good to be familiar with compiler optimizations so you know these themes.
    - (It will help you hand tune code as well)
  - It's good to be familiar with compiler optimizations so you know what they will do with certainty for you
  - Run the different optimization levels is a good skill for new programmers to know about.



https://en.wikipedia.org/wiki/Optimizing_compiler

Goal(s) for today

What you're going to learn today

- Today this talk is a 'grab-bag' of optimization design strategies that may (or may not) improve the performance of your code.
  - At the least, you'll know a few strategies that exist and that you can try to apply to your code today!

Pretend these seats are filled :)
https://pixnio.com/free-images/2017/03/11/2017-03-11-16-47-11-550x413.jpg

Warning -- this talk does include occasional performance numbers.
They are very small 'microbenchmarks' for learning.

Please validate on your architecture on data sets relevant to your program

E	Rated 'E' For Everyone!
	(Yup, let's just do our best to make C++ fun for everyone involved)

Optimization Patterns
(Or really strategies/trade-offs)

Optimization Patterns/Strategies/Trade-offs (1/2)

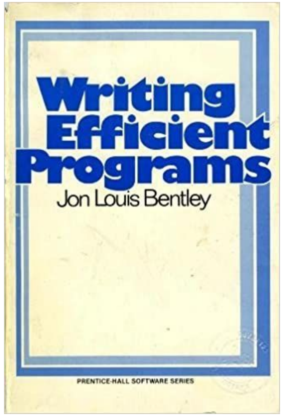
- ‘Patterns’ are ‘blueprints’ or ‘recipes’ that might help solve a problem
- When it comes to optimizations, I think there are a few strategies that can be useful
  - It’s probably more accurate to however describe these as ‘strategies’ or ‘trade-offs’ for obtaining more of something (where ‘more’ today is usually faster execution).
- How I determine a pattern, needs further academic formalization -- I’m not necessarily looking for bit hacks (e.g. a*=2 versus a << 2)
  - But rather opportunities where I am trading **space** for **time**.

Optimization Patterns/Strategies/Trade-offs (2/2)

- ‘Patterns’ are ‘ … problem
- When it comes … tegies that can be useful
  - It’s probably … r ‘trade-offs’ for obtaining mo … cution).
- How I determi … ation -- I’m not necessarily loo …
  - But rather op …

Let me summarize this for you in the next slide(s)

(Note: I’ll run through the next 20 or so slides quickly and you can review them in detail later)



- Space-for-Time Rules
  1. Data Structure Augmentation
  2. Store Precomputed Results
  3. Caching
- Time-for-Space Rules
  1. Packing
  2. Interpreters
- Loop Rules
  1. Code Motion Out of Loops
  2. Combining Tests
  3. Loop Unrolling
  4. Transfer-Driven Loop Unrolling
  5. Unconditional Branch Removal
  6. Loop Fusion
- Logic Rules
  1. Exploit Algebraic Identities
  2. Short-Circuit Monotone Functions
  3. Reorder Tests
  4. Precompute Logical Functions
  5. Control Variable Elimination
- Procedure Design Rules
  1. Collapse Procedure Hierarchies
  2. Exploit Common Cases
  3. Use Coroutines
  4. Transform Recursive Procedures
  5. Use Parallelism
- Expression Rules
  1. Initialize Data Before Runtime
  2. Exploit Algebraic Identities
  3. Eliminate Common Subexpressions
  4. Combine Paired Computation
  5. Exploit Word Parallelism

From John Bentley's Rules of Performance

Next few slides based off of MIT's Performance Engineering course and my 2020 Performance Engineering course

Trade-offs

There are a few key trade-offs we can make on data structures:

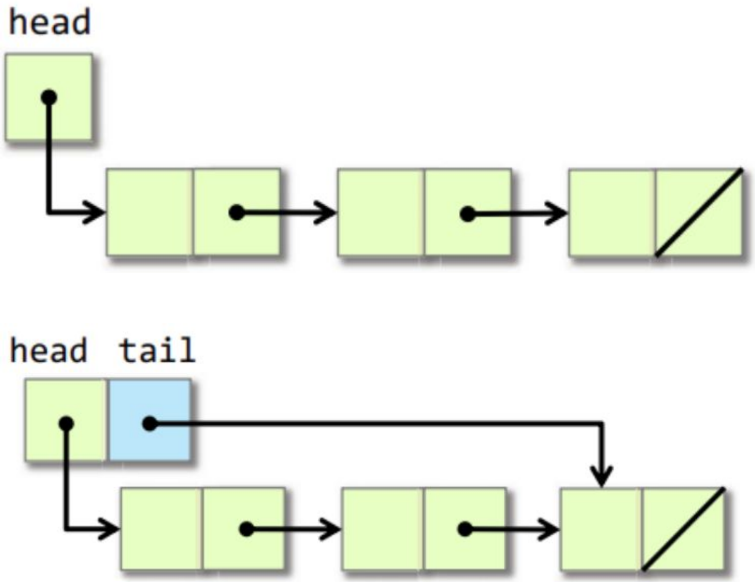
- Space-for-time
- Time for Space
- Space and Time

As I sometimes say, “Computer Science is all about understanding trade-offs” - Mike 

- (And sometimes--you are lucky enough to get both space and time benefits!)

Modifying Data - Space-for-time | Data Structure Augmentation (1/2)

- You can add information to a data structure to make common operations faster
  - e.g. Singly Linked List ‘append’
  - Normally appending requires walking the entire linked list and appending at the end of the linked list a new node
  - Can be spend up by adding a ‘tail’ pointer to directly access the tail



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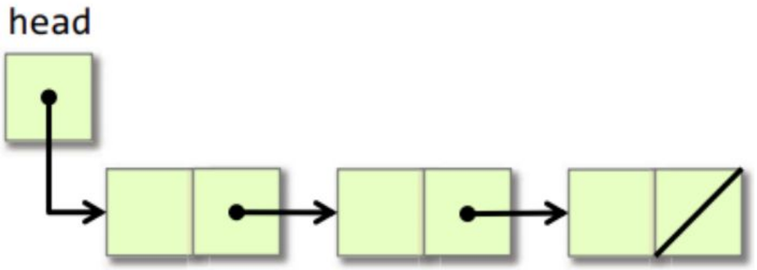
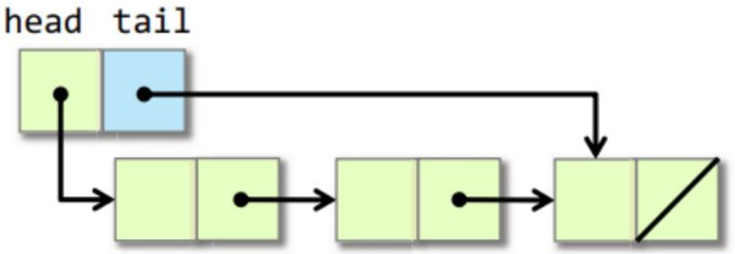
  - Can be spend up by adding a ‘tail’ pointer to directly access the tail
    - Small memory cost overall of maintaining one additional pointer

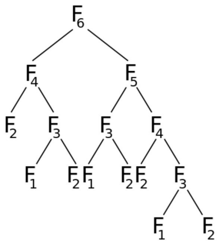





```
class LinkedList
{
private:
    node* m_head;
    node* m_tail;
```

Modifying Data - Space-for-time | Store Pre-computed Result (1/3)

- The example on the right shows computing the ‘nth’ fibonacci number
  - And we compute the result multiple times throughout our program
  - This operation costs O(2^N) time
    - (or about 10 seconds on my machine running this program
    - The reason is we are recomputing the same results frequently.



Recursion tree for Fibonacci of 6

```c
// Compile: gcc fib.c -o fib
// RUn with: time ./fib
#include <stdio.h>

long fib(long n){
    if(n<=1){
        return 1;
    }
    // Recursive call
    return fib(n-1) + fib(n-2);
}


int main(){

    const long NthNumberToCompute = 45;

    long fibComputation1 = fib(NthNumberToCompute);
    long fibComputation2 = fib(NthNumberToCompute);

    printf("fibComputation1: %ld\n",fibComputation1);
    printf("fibComputation2: %ld\n",fibComputation2);

    return 0;
}
```

```
mike:code$ time ./fib
fibComputation1: 1836311903
fibComputation2: 1836311903

real    0m9.204s
user    0m9.203s
sys     0m0.000s
```

Modifying Data - Space-for-time | Store Pre-computed Result (2/3)

- We can speed up Fibonacci by caching the result (Memoization)
  - This optimization works because we:
    - Have a generally expensive function
    - The argument space is relatively small (1 argument of integer type)
    - Function has no side effects
    - Function is deterministic
- Drumroll for the result....

```c
// Compile: gcc fib_table.c -o fib_table
// RUn with: time ./fib_table
#include <stdio.h>

#define PRECOMPUTED_VALUES 100
long FIB_TABLE[PRECOMPUTED_VALUES];

long initialize_table(){
    for(long i= 0; i < PRECOMPUTED_VALUES; i++){
        // Store as a sentinal value so we know
        // it has not been precomputed
        FIB_TABLE[i] = -1;
    }
}


long fib_memo(long n){
    // lookup value first and return result
    // if it has not been previously computed
    if(FIB_TABLE[n] != -1){
        return FIB_TABLE[n];
    }
    // base case
    if(n<=1){
        FIB_TABLE[n] = 1;
        return 1;
    }
    // Recursive call
    FIB_TABLE[n] = fib_memo(n-1) + fib_memo(n-2);
    return FIB_TABLE[n];
}


int main(){

    const long NthNumberToCompute = 45;
    // Setup our table
    initialize_table();

    long fibComputation1 = fib_memo(NthNumberToCompute);
    long fibComputation2 = fib_memo(NthNumberToCompute);

    printf("fibComputation1: %ld\n",fibComputation1);
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```
mike:code$ time ./fib_table
fibComputation1: 1836311903
fibComputation2: 1836311903

real	0m0.002s
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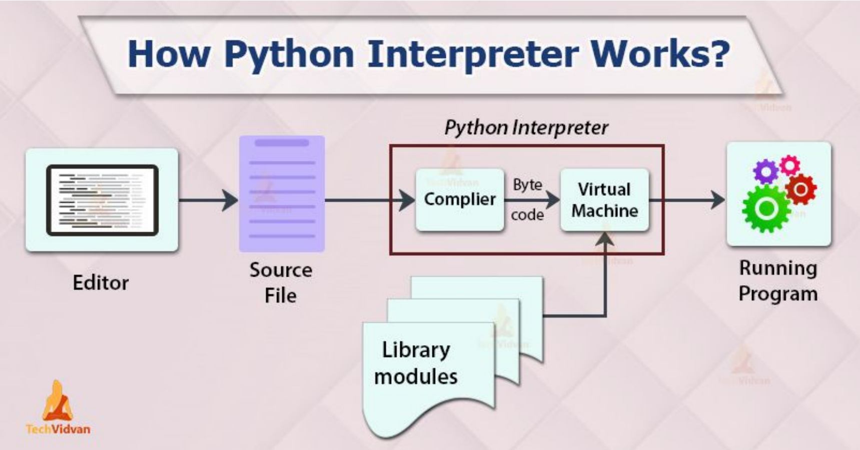
}
```

Modifying Data - Time-for-Space | Packing/Compression

- Reduce space of data by storing processed results
  - e.g. Data compression(e.g. .zip, .rar) by eliminating repetitions (LZ77)
  - Just a cool example: https://www.youtube.com/watch?v=2NBG-sKFaB0
- Useful on embedded devices for example
- Or if you are trying to limit bandwidth usage on networked applications
- Other practical tips
  - Use smaller data sizes
    - i.e. If your range is only 0-255, use a char not an 'int' --
      - (Aside: very common use case for storing RGB color values for instance, and frequently I see folks use 'int')

Modifying Data - Time-for-Space | Interpreters

- e.g. Python
  - It's an interpreted language (reads byte code)
  - No need to generate binaries (.o, .exe, etc.) files, just need the source code!
  - The language thus describes the computation, no need to store opcodes
- Does not have to be a full language either
  - Could be reading in data from a file during run-time for example as opposed to storing in the binary.



Modifying Data - Space-and-Time | Packing (1/2)

- We try to store (or encode) more data into a machine word
  - Why does it make things faster?
    - This results in less ‘fetches’ to memory for data.
    - (This is also more space efficient!)
- Here’s an example using ‘bit fields’ in C.

```c
// 96-bit representation of date
// 1 int is 32 bits (4 bytes)
// 3 ints thus is 3*32 = 96 bits.
typedef struct{
  int year;
  int month;
  int day;
} date_t;
```

```c
// 22-bit representation of date
typedef struct{
    int year: 13; // 2^13 or 8192 years [-4096-4095]
    int month: 4; // 4 bits is 2^4=16 for months
    int day: 5;   // 5 bits--months of 32 days max
} date_t;
```

(Slight caveat, that compiler may ‘pad’ struct to align it better to say 32-bits)

Modifying Data - Space-and-Time | Packing (2/2)

- We try to store (or encode) more data into a machine word
  - Why does it make things faster?
    - This results in less ‘fetches’ to memory for data.
    - (This is also more space efficient!)
- Here’s an example using ‘bit fields’ in C.

```
// 96-bit representation of date
// 1 int is 32 bits (4 bytes)
// 3 ints thus is 3*32 = 96 bits.
typedef struct{
  int year;
  int month;
  int day;
} date_t;
```

```
// 22-bit representation of date
typedef struct{
    int year: 13; // 2^13 or 8192 years [-4096-4095]
    int month: 4; // 4 bits is 2^4=16 for months
    int day: 5;   // 5 bits--months of 32 days max
} date_t;
```

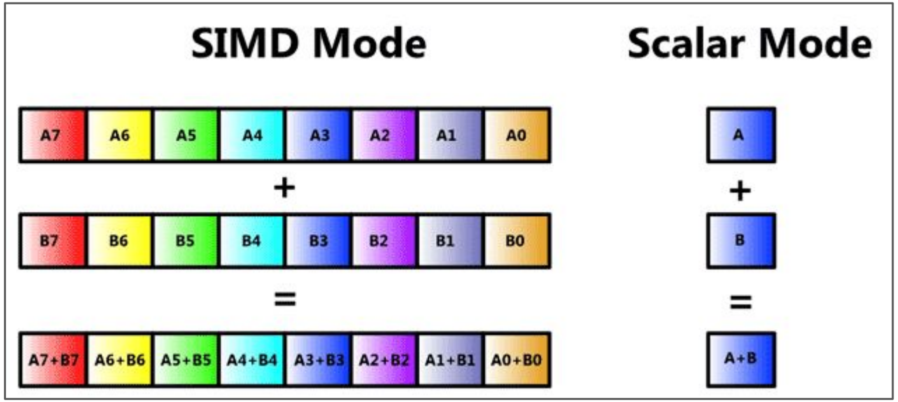
(Slight caveat, that compiler may ‘pad’ struct to align it better to say 32-bits)

Second caveat--decoding (unpacking) may take more time--in which case the optimization may involve more work if you have to decode before using this data.

More: https://compileroptimizations.com/category/bitfield_optimization.htm

Modifying Data - Space-and-Time | SIMD

- Single Instruction Multiple Data
  - Execute a single operation on multiple data items
  - Both faster and less storage
- Can be used
  - If same operation is used on all data items.
  - (We'll explore this a bit more later in the course!)



Modifying the Code Structure

Modifying Code

There are a few key trade-offs we can make on how we structure our code:

- Loops
- Logic
- Functions (Procedures)
- Expressions
- Parallelism
    - (We'll discuss in future lecture as they are more architecture specific)

Some of these are common enough, our compilers can actually assist us as well!

Modifying Code | Loops

- Loops are especially important to optimize?
- Why--because we spend so much of our time executing in loops
- Let’s look at a few optimizations within loops
  - Code Motion
  - Sentinel Loop Exit Test
  - Loop Unrolling
  - Partial Loop Unrolling
  - Loop Fusion

Modifying Code | Loops -- Code Motion (1/3)

- Move code outside of loop that does not need to be recomputed.
  - More on lazy code motion: https://www.cs.cornell.edu/courses/cs6120/2019fa/blog/lazy-code-motion/)

```c
// gcc code_motion_off -o code_motion_off
// time ./code_motion_off
#define ITERATIONS 1000000


double approx_pi(){
    return 22.0/7.0;
}

int main(){

    double circumferences[ITERATIONS];
    for(int i=0; i < ITERATIONS; i++){
        // 2 * PI * r = circumference
        circumferences[i] = 2*approx_pi()*i;
    }

    return 0;
}
```

```c
// gcc code_motion_on -o code_motion_on
// time ./code_motion_on
#define ITERATIONS 1000000


double approx_pi(){
    return 22.0/7.0;
}

int main(){

    double circumferences[ITERATIONS];
    double PI_times_2 = 2*approx_pi();
    for(int i=0; i < ITERATIONS; i++){
        // 2 * PI * r = circumference
        circumferences[i] = PI_times_2*i;
    }

    return 0;
}
```

approx_pi() is used to generate some work for the benchmark, not because I don't like writing 3.1415

Modifying Code | Loops -- Code Motion (2/3)

- Move code outside of loop that does not need to be recomputed.
  - More on lazy code motion: https://www.cs.cornell.edu/courses/cs6120/2019fa/blog/lazy-code-motion/)

```
// gcc code_motion_of
// time ./code_motion
#define ITERATIONS 10


double approx_pi(){
    return 22.0/7.0;
}

int main(){
```

Careful however! Experimental results show code motion made this example slower!

Why could this be?

```
mike:code$ gcc code_motion_off.c -o code_motion_off
mike:code$ time ./code_motion_off

real    0m0.009s
user    0m0.000s
sys     0m0.009s
```

```
    return 0;
}
```

```
mike:code$ gcc code_motion_on.c -o code_motion_on
mike:code$ time ./code_motion_on

real    0m0.019s
user    0m0.011s
sys     0m0.008s
mike:code$ time ./code_motion_on
```

```
int main(){
...
    return 0;
}
```

approx_pi() is used to generate some work for the benchmark, not because I don't like writing 3.1415

Modifying Code | Loops -- Code Motion (3/3)

- Move code outside of loop that does not need to be recomputed.
  - More on lazy code motion: https://www.cs.cornell.edu/courses/cs6120/2019fa/blog/lazy-code-motion/)

Careful however! Experimental results show code motion made this example slower!

Why could this be?

- Memory fetches (reads of variable) might be more expensive!
  - Actual computation is thus not that costly to perform each iteration (sqrt, or some other operation may be however)
- We need to see the assembly if the compiler would actually perform this optimization!

```
mike:code$ gcc code_motion_off.c -o code_motion_off
mike:code$ time ./code_motion_off

real    0m0.009s
user    0m0.000s
sys     0m0.009s
```

```
mike:code$ gcc code_motion_on.c -o code_motion_on
mike:code$ time ./code_motion_on

real    0m0.019s
user    0m0.011s
sys     0m0.008s
mike:code$ time ./code_motion_on
```

Modifying Code | Loops -- Sentinel Loop Exit Test

- Exiting early is another way to save on performance--no need to continue iterating through the entire collection when a value is found.

```c
// Return 'some' index of a character found
int indexOf(char* str,char ch, int size){
    int index = -1;
    for(int i =0; i < size; i++){
        if(str[i]==ch){
            index =i;
        }
    }
    return -1;
}
```

```c
int indexOf(char* str,char ch, int size){
    for(int i =0; i < size; i++){
        if(str[i]==ch){
            return i;
        }
    }

    return -1;
}
```

Modifying Code | Loops -- Loop Unrolling (elimination of the loop)

- Small loops can be 'unrolled' to avoid comparison computations.
    - Generally something the compiler will figure out for you--but you can control this by doing it yourself.:w

```c
// gcc loop_unroll.c -o loop_unroll

int main(){

    // We can unroll this loop
    int sum =0;
    int A[4] = {1,2,3,4};

    for(int i=0; i < 4; i++){
        sum = sum + A[i];
    }
    // to...
    sum = A[0] + A[1] + A[2] + A[3];


    return 0;
}
```

Modifying Code | Loops -- Partial Loop Unrolling

- A similar idea where we can partially unroll the loop
  - Can be especially powerful when combined with SIMD

```c
// gcc partial_loop_unroll.c -o partial_loop_unroll

int main(){

    // We can partially unroll this loop
    int sum =0;
    int A[4] = {1,2,3,4};

    for(int i=0; i < 4; i++){
        sum = sum + A[i];
    }
    // to...
    for(int i=0; i < 4; i+=2){
        sum = sum + A[i];
        sum = sum + A[i+1];
    }


    return 0;
}
```

Modifying Code | Loops -- Loop Fusion

- We can merge loops together that are otherwise performing independent computations.

```
for (i = 0; i < 300; i++)
  a[i] = a[i] + 3;

for (i = 0; i < 300; i++)
  b[i] = b[i] + 4;
```

Below is the code fragment after loop fusion.

```
for (i = 0; i < 300; i++)
  {
    a[i] = a[i] + 3;
    b[i] = b[i] + 4;
  }
```

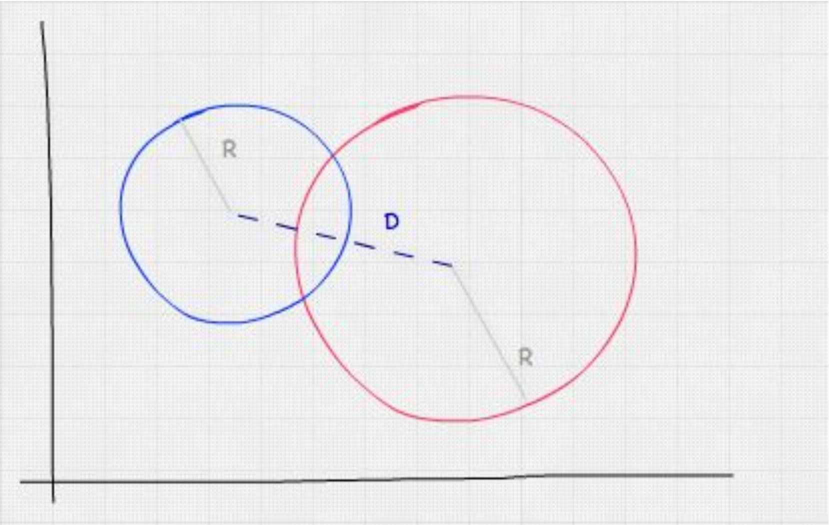
Modifying Code | Logical Expression - Strength Reduction

- Occasionally we can make a better substitution that logically gives us the same control flow

`sqrt(x) > 0`	`x !=0`
`sqrt(x*x + y*y) < sqrt(a*a + b*b)`	`x*x + y*y < a*a + b*b`
`ln(A) + ln(B)`	`ln(A*B)`
`sin(x)*sin(x) + cos(x)*cos(x)`	`1`

Modifying Code | Logic - Reorder Tests (1/2)

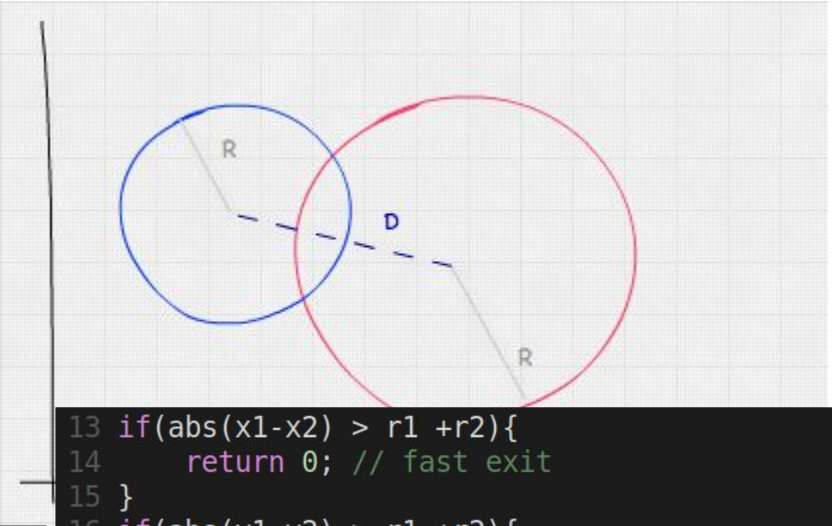
- Logical tests should be arranged so that inexpensive and often successful tests precede expensive and rarely successful tests.




```
// Checks if a collision occurred
if( sqrt(sqr(x1-x2) + sqr(y1-y2)) < (r1 + r2)){
    return 1;
}else{
    return 0;
}
```

Modifying Code | Logic - Reorder Tests (2/2)

- Logical tests should be arranged so that inexpensive and often successful tests precede expensive and rarely successful tests.




```
// Checks if a collision occurred
if( sqrt(sqr(x1-x2) + sqr(y1-y2)) < (r1 + r2)){
    return 1;
}else{
    return 0;
}
```

```
if(abs(x1-x2) > r1 +r2){
    return 0; // fast exit
}
if(abs(y1-y2) > r1 +r2){
    return 0; // fast exit
}
if( sqrt(sqr(x1-x2) + sqr(y1-y2)) < (r1 + r2))
    return 1;
}else{
    return 0;
}
```

Modifying Code | Procedures - Inlining

- Eliminates function call overhead by moving small functions into body of code.
- Also provides further optimization opportunities for compilers to perform after the inlining takes place.
  - Generally speaking this is one of the biggest optimizations, because we often (not always) optimize on a function level.
  - https://compileroptimizations.com/category/function_inlining.htm

```
int add (int x, int y)
{
  return x + y;
}

int sub (int x, int y)
{
  return add (x, -y);
}
```

Expanding add() at the call site in sub() yields:

```
int sub (int x, int y)
{
  return x + -y;
}
```

which can be further optimized to:

```
int sub (int x, int y)
{
  return x - y;
}
```

Modifying Code | Expression Rules - Constant Propogation

- Simply propagate the result
  - This may also save us on both time and space of computing and storing intermediate values.

In the code fragment below, the value of x can be propagated to the use of x.

```
x = 3;
y = x + 4;
```

Below is the code fragment after constant propagation and constant folding.

```
x = 3;
y = 7;
```

Modifying Code | Expression Rules - Compile-Time Initialization

- If a value is constant, we can make a compile-time constant
  - We'll see 'constexpr' in C++
- Saves the effort of computation
- This may allow us to perform further constant propagation
- Again enables further optimizations!

```
// constexpr function for product of two numbers.
// By specifying constexpr, we suggest compiler to
// to evaluate value at compile time
constexpr int product(int x, int y)
{
    return (x * y);
}

int main()
{
    const int x = product(10, 20);
    cout << x;
    return 0;
}
```

https://www.geeksforgeeks.org/understanding-constexper-specifier-in-c/

Vec3 Class

Example of more performance patterns and how to possibly iterate through optimizations

VecN class

- So to ground us in some simple examples to learn from, let’s start with a class like this
  - It’s an ‘n-element’ vector where we have a few member functions
  - We’ll use a std::vector to store individual elements.
  - The data structure is also templated so that we can consider storing any type.

```cpp
// g++ -g -Wall -std=c++20 vecN.cpp -o prog && ./prog
#include <iostream>
#include <vector>

// Generic n-dimensional mathematical vector
template<typename T>
struct VecN{
  // ========== Member Variables ==============
  // Store indidividual components
  std::vector<T> components;

  // ========== Member Functions ==============
  // Constructor
  VecN(size_t elements);
  // Print out the components
  void Print() const;
  // Add some components
  VecN<T>& operator+=(const VecN<T>& rhs);
};
```

Optimization Strategy/Pattern #1: **Caching**

A run-time space versus run-time trade-off

Vec3N Member Functions

- I've gone ahead and implemented three member functions

```cpp
// Constructor
template<typename T>
  VecN<T>::VecN(size_t elements){
  // Initialize components
  for(size_t i=0; i < elements; ++i){
    components.push_back(i);
  }
}

// Print
template<typename T>
void VecN<T>::Print() const{
  for(size_t i=0; i < components.size(); ++i){
    std::cout << components.at(i) << "." << std::endl;
  }
}

// generic addition overload
template<typename T>
  VecN<T>& VecN<T>::operator+=(const VecN<T>& rhs){
    for(size_t i=0; i < components.size(); ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Recomputation

- It appears I am recomputing work very frequently however!
- Question to Audience: Anyone spot where?
    - (ans: next slide)

```
// Constructor
template<typename T>
  VecN<T>::VecN(size_t elements){
  // Initialize components
  for(size_t i=0; i < elements; ++i){
    components.push_back(i);
  }
}

// Print
template<typename T>
void VecN<T>::Print() const{
  for(size_t i=0; i < components.size(); ++i){
    std::cout << components.at(i) << "." << std::endl;
  }
}

// generic addition overload
template<typename T>
  VecN<T>& VecN<T>::operator+=(const VecN<T>& rhs){
    for(size_t i=0; i < components.size(); ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Recomputation

- It appears I am recomputing work very frequently however!
- Question to Audience: Anyone spot where?
  - I'm constantly calling components.size() every iteration of every loop
  - For a 'print' function (which is likely const) why would I need to do this?

```cpp
// Constructor
template<typename T>
  VecN<T>::VecN(size_t elements){
  // Initialize components
  for(size_t i=0; i < elements; ++i){
    components.push_back(i);
  }
}

// Print
template<typename T>
void VecN<T>::Print() const{
  for(size_t i=0; i < components.size(); ++i){
    std::cout << components.at(i) << " " << std::endl;
  }
}

// generic addition overload
template<typename T>
  VecN<T>& VecN<T>::operator+=(const VecN<T>& rhs){
    for(size_t i=0; i < components.size(); ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Caching

- So here's the adjustment we can make before the loop.
    - For vectors of very large 'n' this may make some difference having 'len' directly on the stack (we'll have to measure)
- Note: pragmatically -- for a vector -- .size() is just a lookup and already optimized -- this function is probably 'inlined'.
    - Presumably for a 'graph' or some more complicated linked data structure traversal it may be worth performing this specific optimization.

```
// Constructor
template<typename T>
  VecN<T>::VecN(size_t elements){
  // Initialize components
  for(size_t i=0; i < elements; ++i){
    components.push_back(i);
  }
}

// Print
template<typename T>
void VecN<T>::Print() const{
  size_t len = components.size();
  for(size_t i=0; i < len; ++i){
    std::cout << components.at(i) << "." << std::endl;
  }
}

// generic addition overload
template<typename T>
  VecN<T>& VecN<T>::operator+=(const VecN<T>& rhs){
  size_t len = components.size();
  for(size_t i=0; i < len; ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Measuring Optimizations

Measurements (1/2)

- So in order to know if our optimization strategy (caching) worked -- we need to measure each strategy in an experiment
- Here's an example using 'time' running 1_000_000 iterations of add.

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 vecN.cpp -o prog && time ./prog
0.
1000001.
2000002.

real    0m0.025s
user    0m0.025s
sys     0m0.000s
```

No optimization -- takes about 0.025 seconds

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 caching1.cpp -o prog && time ./prog
0.
1000001.
2000002.

real    0m0.017s
user    0m0.016s
sys     0m0.000s
```

Caching a bit faster -- perhaps small enough that our computation is noise?

Measurements (2/2)

- So in order to know if our optimization strategy (cachin
  to measure each strategy in an experiment
- Here's an example using 'time' running 1_000_000 iteratio add.

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 vecN.cpp -o prog && e ./prog
0.
1000001.
2000002.

real    0m0.025s
user    0m0.025s
sys     0m0.000s
```

No optimization -- takes about 0.025 seconds

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 caching1.cpp -o prog && time ./prog
0.
1000001.
2000002.

real    0m0.017s
user    0m0.016s
sys     0m0.000s
```

Caching a bit faster -- perhaps small enough that our computation is noise?

Let's see if we can tease out more information from this using a different profiler

perf profiler

- We need a more fine grained measurement to try to understand what our optimization strategy did -- otherwise again it may just be noise.
    - The perf profiler is a well known tool on linux, and your platform may otherwise provide other useful tools

```
PERF(1)                    perf Manual                    PERF(1)

NAME
       perf - Performance analysis tools for Linux

SYNOPSIS
       perf [--version] [--help] [OPTIONS] COMMAND [ARGS]
```


On Ubuntu you can install with something like: `sudo apt-get install linux-tools-5.4.0-149-generic` (Note: This may change based on your kernel)

Observing Perf

- So from this output, it appears that we do have:
  - Less instructions executed
  - fewer cpu cycles
  - fewer branches
  - (oddly more branch-misses though!)

No optimization

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 vecN.cpp -o prog
mike:2023_italian_cpp$ sudo perf stat ./prog
0.
1000001.
2000002.

 Performance counter stats for './prog':

          20.91 msec task-clock                #    0.988 CPUs utilized
              0      context-switches          #    0.000 K/sec
              0      cpu-migrations            #    0.000 K/sec
            117      page-faults               #    0.006 M/sec
     83,507,688      cycles                    #    3.994 GHz
    213,323,341      instructions              #    2.55  insn per cycle
     31,578,068      branches                  # 1510.467 M/sec
         16,847      branch-misses             #    0.05% of all branches

    0.021152750 seconds time elapsed

    0.021166000 seconds user
    0.000000000 seconds sys
```

Caching

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 caching1.cpp -o prog
mike:2023_italian_cpp$ sudo perf stat ./prog
0.
1000001.
2000002.

 Performance counter stats for './prog':

          18.78 msec task-clock                #    0.983 CPUs utilized
              0      context-switches          #    0.000 K/sec
              0      cpu-migrations            #    0.000 K/sec
            118      page-faults               #    0.006 M/sec
     76,223,347      cycles                    #    4.059 GHz
    165,337,456      instructions              #    2.17  insn per cycle
     25,579,300      branches                  # 1362.301 M/sec
        249,690      branch-misses             #    0.98% of all branches

    0.019094558 seconds time elapsed

    0.019133000 seconds user
    0.000000000 seconds sys
```

Perf - was it worth it?

- One of the first questions we should have even asked was if it was worth complicating our code
  - (i.e. remember Knuth's warning?)
- Stepping back, we can generate a 'perf report' by 'recording' execution of our program.

```
Samples: 216  of event 'cycles', Event count (approx.): 84105708
Overhead  Command  Shared Object        Symbol
  39.14%  prog     prog                 [.] VecN<int>::operator+=
  30.17%  prog     prog                 [.] std::vector<int, std::allocator<int> >::size
  12.35%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
  11.72%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
   3.31%  prog     prog                 [.] main
   0.54%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a2865b
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a12cee
   0.50%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a288b6
   0.48%  prog     ld-2.27.so           [.] strcmp
   0.46%  prog     libstdc++.so.6.0.29  [.] std::locale::operator=
   0.25%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a6e62a
   0.03%  perf     [kernel.kallsyms]    [k] 0xffffffffb52d1c30
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb483ca5c
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb48104be
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ada
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ad8
```

No optimization

```
Samples: 127  of event 'cycles', Event count (approx.): 66108775
Overhead  Command  Shared Object        Symbol
  54.21%  prog     prog                 [.] VecN<int>::operator+=
  15.00%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
  10.98%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
   8.97%  prog     prog                 [.] main
   5.78%  prog     prog                 [.] std::vector<int, std::allocator<int> >::size
   1.19%  prog     [kernel.kallsyms]    [k] filemap_map_pages
   1.17%  prog     [kernel.kallsyms]    [k] change_protection_range
   0.99%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.94%  prog     ld-2.27.so           [.] do_lookup_x
   0.75%  prog     [kernel.kallsyms]    [k] strnlen_user
   0.01%  perf     [kernel.kallsyms]    [k] intel_pmu_enable_all
   0.00%  perf     [kernel.kallsyms]    [k] native_write_msr
```

Caching

Perf - was it worth it?

- The perf report tells us where we spent our time
- At first glance it looks like we made things worse!
  - (i.e. 39.14% is less than 54.21%)
  - (next slide)

```
Samples: 216  of event 'cycles', Event count (approx.): 84105708
Overhead  Command  Shared Object        Symbol
  39.14%  prog     prog                 [.] VecN<int>::operator+=
  30.17%  prog     prog                 [.] std::vector<int, std::allocator<int> >::size
  12.35%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
  11.72%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
   3.31%  prog     prog                 [.] main
   0.54%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a2865b
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a12cee
   0.50%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a288b6
   0.48%  prog     ld-2.27.so           [.] strcmp
   0.46%  prog     libstdc++.so.6.0.29  [.] std::locale::operator=
   0.25%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a6e62a
   0.03%  perf     [kernel.kallsyms]    [k] 0xffffffffb52d1c30
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb483ca5c
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb48104be
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ada
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ad8
```

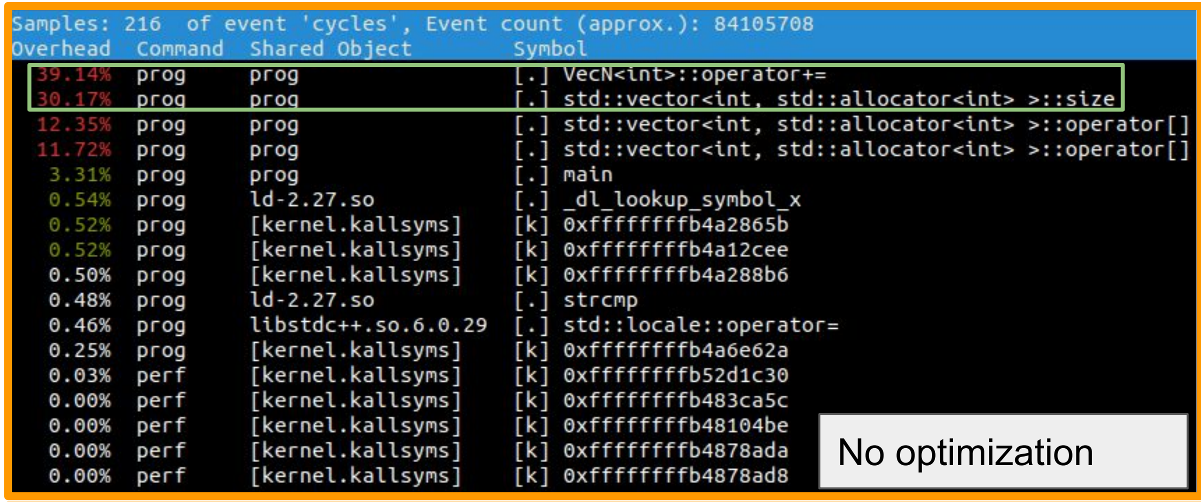
No optimization

```
Samples: 127  of event 'cycles', Event count (approx.): 66108775
Overhead  Command  Shared Object       Symbol
  54.21%  prog     prog                [.] VecN<int>::operator+=
  15.00%  prog     prog                [.] std::vector<int, std::allocator<int> >::operator[]
  10.98%  prog     prog                [.] std::vector<int, std::allocator<int> >::operator[]
   8.97%  prog     prog                [.] main
   5.78%  prog     prog                [.] std::vector<int, std::allocator<int> >::size
   1.19%  prog     [kernel.kallsyms]   [k] filemap_map_pages
   1.17%  prog     [kernel.kallsyms]   [k] change_protection_range
   0.99%  prog     ld-2.27.so          [.] _dl_lookup_symbol_x
   0.94%  prog     ld-2.27.so          [.] do_lookup_x
   0.75%  prog     [kernel.kallsyms]   [k] strnlen_user
   0.01%  perf     [kernel.kallsyms]   [k] intel_pmu_enable_all
   0.00%  perf     [kernel.kallsyms]   [k] native_write_msr
```

Caching

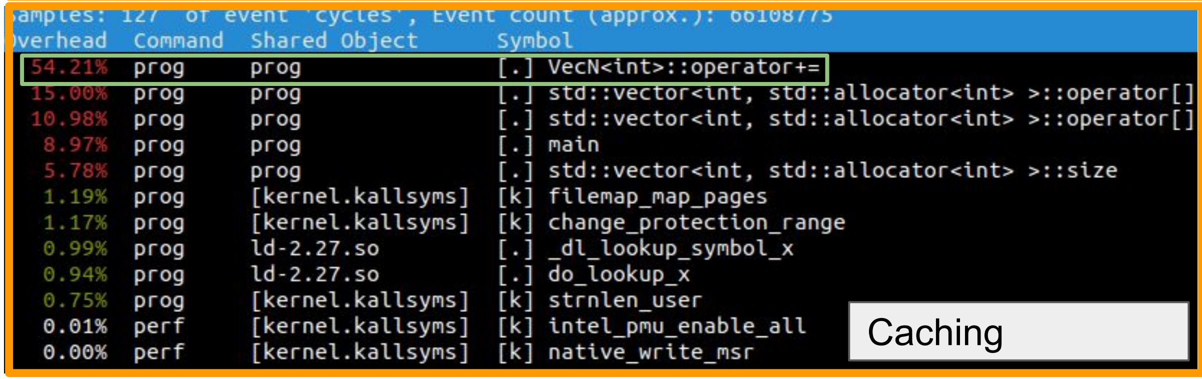
Perf - was it worth it?

- The perf report tells us where we spent our time
- At first glance it looks like we made things worse!
  - (i.e. 39.14% is less than 54.21%)
  - Consider however, there is no call to ‘std::vector<...>size’ on the next line however
  - Looks like we have trimmed some time!



```
Samples: 216  of event 'cycles', Event count (approx.): 84105708
Overhead  Command  Shared Object        Symbol
  39.14%  prog     prog                 [.] VecN<int>::operator+=
  30.17%  prog     prog                 [.] std::vector<int, std::allocator<int> >::size
  12.35%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
  11.72%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
   3.31%  prog     prog                 [.] main
   0.54%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a2865b
   0.52%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a12cee
   0.50%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a288b6
   0.48%  prog     ld-2.27.so           [.] strcmp
   0.46%  prog     libstdc++.so.6.0.29  [.] std::locale::operator=
   0.25%  prog     [kernel.kallsyms]    [k] 0xffffffffb4a6e62a
   0.03%  perf     [kernel.kallsyms]    [k] 0xffffffffb52d1c30
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb483ca5c
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb48104be
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ada
   0.00%  perf     [kernel.kallsyms]    [k] 0xffffffffb4878ad8
```

No optimization



```
Samples: 127  of event 'cycles', Event count (approx.): 66108775
Overhead  Command  Shared Object        Symbol
  54.21%  prog     prog                 [.] VecN<int>::operator+=
  15.00%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
  10.98%  prog     prog                 [.] std::vector<int, std::allocator<int> >::operator[]
   8.97%  prog     prog                 [.] main
   5.78%  prog     prog                 [.] std::vector<int, std::allocator<int> >::size
   1.19%  prog     [kernel.kallsyms]    [k] filemap_map_pages
   1.17%  prog     [kernel.kallsyms]    [k] change_protection_range
   0.99%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.94%  prog     ld-2.27.so           [.] do_lookup_x
   0.75%  prog     [kernel.kallsyms]    [k] strnlen_user
   0.01%  perf     [kernel.kallsyms]    [k] intel_pmu_enable_all
   0.00%  perf     [kernel.kallsyms]    [k] native_write_msr
```

Caching

Was Caching a win?

- Now, sometimes if we're not getting a huge performance boost, we might be solving the wrong problem or using the wrong technique.
    - As mentioned on my aside, caching is probably not a huge performance boost here.
    - So there's a different optimization strategy we can try

```
// Constructor
template<typename T>
  VecN<T>::VecN(size_t elements){
  // Initialize components
  for(size_t i=0; i < elements; ++i){
    components.push_back(i);
  }
}

// Print
template<typename T>
void VecN<T>::Print() const{
  size_t len = components.size();
  for(size_t i=0; i < len; ++i){
    std::cout << components.at(i) << "." << std::endl;
  }
}

// generic addition overload
template<typename T>
  VecN<T>& VecN<T>::operator+=(const VecN<T>& rhs){
  size_t len = components.size();
  for(size_t i=0; i < len; ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Optimization Strategy/Pattern #2:
Compile-Time Computation

A compile-time space versus run-time computation trade-off

Compile-time

- Ultimately we always trade time and space for performance
    - But in C++ we can choose to make that trade-off at compile-time and run-time as well!
    - Let’s optimize any computation by templating our function
        - Afterall, are we going to change the ‘size’ of the n-dimensional vector?
            - (For this example, the answer is no)

```
// Generic n-dimensional mathematical vector
template<typename T, size_t length>
struct VecN{
  // ========== Member Variables ==============
  // Store indidividual components
  std::vector<T> components;

  // ========== Member Functions ==============
  // Constructor
  VecN();
  // Print out the components
  void Print();
  // Add some components
  VecN<T,length>& operator+=(const VecN<T,length>& rhs);
};
```

Compile-time

- Observe we now know the length at compile-time and no longer have to query the length at run-time for our loops

```cpp
// g++ -g -Wall -std=c++20 vecN.cpp -o prog && ./prog
#include <iostream>
#include <vector>

// Generic n-dimensional mathematical vector
template<typename T>
struct VecN{
  // ========== Member Variables ==============
  // Store indidividual components
  std::vector<T> components;

  // ========== Member Functions ==============
  // Constructor
  VecN(size_t elements);
  // Print out the components
  void Print() const;
  // Add some components
  VecN<T>& operator+=(const VecN<T>& rhs);
};
```

```cpp
// g++ -g -Wall -std=c++20 compile_time.cpp -o prog && ./prog
#include <iostream>
#include <vector>

// Generic n-dimensional mathematical vector
template<typename T, size_t length>
struct VecN{
  // ========== Member Variables ==============
  // Store indidividual components
  std::vector<T> components;

  // ========== Member Functions ==============
  // Constructor
  VecN();
  // Print out the components
  void Print();
  // Add some components
  VecN<T,length>& operator+=(const VecN<T,length>& rhs);
};
```

Compile-Time Results

- Our fastest result yet!
- And we can try something else after our realization that length does not change
  - (an age old tradeoff...)

Compile-time

```
mike:2023_italian_cpp$ sudo perf stat ./prog
0.
1000001.
2000002.

 Performance counter stats for './prog':

             15.22 msec task-clock                #    0.985 CPUs utilized
                 0      context-switches          #    0.000 K/sec
                 0      cpu-migrations            #    0.000 K/sec
               118      page-faults               #    0.008 M/sec
        60,718,858      cycles                    #    3.990 GHz
       145,308,561      instructions              #    2.39  insn per cycle
        23,575,716      branches                  # 1549.215 M/sec
            16,618      branch-misses             #    0.07% of all branches

       0.015454034 seconds time elapsed

       0.015474000 seconds user
       0.000000000 seconds sys
```

```
Samples: 41  of event 'cycles', Event count (approx.): 60031268
Overhead  Command  Shared Object      Symbol
  56.94%  prog     prog               [.] VecN<int, 3ul>::operator+=
  13.25%  prog     prog               [.] main
  12.21%  prog     prog               [.] std::vector<int, std::allocator<int> >::operator[]
  10.33%  prog     prog               [.] std::vector<int, std::allocator<int> >::operator[]
   5.12%  prog     [kernel.kallsyms]  [k] kfree
   1.76%  prog     [kernel.kallsyms]  [k] __mod_memcg_state
   0.37%  prog     [kernel.kallsyms]  [k] security_bprm_committed_creds
   0.01%  perf     [kernel.kallsyms]  [k] native_sched_clock
   0.00%  perf     [kernel.kallsyms]  [k] native_write_msr
```

Optimization Strategy/Pattern #3:
Solve the right problem with the right data structure

A classic space vs time data structure trade-off

Choose the right data structure

- Did we really need the capabilities of a vector?
  - (Note: I have to be careful here if we changing the problem)
  - Let's assume I did not however, and my domain (e.g. games) usually have vectors stay the same size (e.g. 3 components) when initialized.
- Note: This is often the best optimization strategy -- try another data structure or algorithm

```cpp
// g++ -g -Wall -std=c++20 array.cpp -o prog && ./prog
#include <iostream>

// Generic n-dimensional mathematical vector
template<typename T, size_t length>
struct VecN{
  // ========== Member Variables ==============
  // Store indidividual components
  T components[length];

  // ========== Member Functions ==============
  // Constructor
  VecN();
  // Print out the components
  void Print();
  // Add some components
  VecN<T,length>& operator+=(const VecN<T,length>& rhs);
};
```

Choose the right data structure

- Faster yet again!
  - (And more important -- consistently faster!)
- But there is something bothering me
  - We are spending lots of time in +=

```
Samples: 100  of event 'cycles', Event count (approx.): 40643887
Overhead  Command  Shared Object        Symbol
  79.08%  prog     prog                 [.] VecN<int, 3ul>::operator+=
  10.68%  prog     prog                 [.] main
   2.34%  prog     [kernel.kallsyms]    [k] unmap_page_range
   1.43%  prog     ld-2.27.so           [.] _dl_relocate_object
   1.43%  prog     ld-2.27.so           [.] _dl_lookup_symbol_x
   0.78%  prog     ld-2.27.so           [.] _dl_debug_initialize
   0.72%  prog     ld-2.27.so           [.] do_lookup_x
   0.72%  prog     libc-2.27.so         [.] init_cacheinfo
   0.71%  prog     ld-2.27.so           [.] malloc
   0.71%  prog     [kernel.kallsyms]    [k] clear_page_erms
   0.71%  prog     [kernel.kallsyms]    [k] get_mem_cgroup_from_mm
   0.53%  prog     [kernel.kallsyms]    [k] get_page_from_freelist
   0.14%  prog     [kernel.kallsyms]    [k] apparmor_bprm_committed_creds
   0.02%  perf     [kernel.kallsyms]    [k] perf_event_addr_filters_exec
   0.00%  perf     [kernel.kallsyms]    [k] native_write_msr
```

```
mike:2023_italian_cpp$ g++ -Wall -std=c++20 array.cpp -o prog
mike:2023_italian_cpp$ sudo perf stat ./prog
0.
1000001.
2000002.

 Performance counter stats for './prog':

              6.66 msec task-clock                #    0.961 CPUs utilized
                 0      context-switches          #    0.000 K/sec
                 0      cpu-migrations            #    0.000 K/sec
               119      page-faults               #    0.018 M/sec
        26,987,099      cycles                    #    4.050 GHz
        64,342,603      instructions              #    2.38  insn per cycle
        11,579,759      branches                  # 1737.654 M/sec
            16,397      branch-misses             #    0.14% of all branches

       0.006930871 seconds time elapsed

       0.006945000 seconds user
       0.000000000 seconds sys
```

(Aside)

- If switching to an array felt like cheating, I did go back to our very first example and just switch to a heap allocated array to see the difference.
    - results were 'noisier' do to the heap allocations (but sometimes still way faster) -- so sometimes we like more stable guarantees on time as well!

```
mike:2023_italian_cpp$ sudo perf stat ./prog
0.
1000001.
2000002.

 Performance counter stats for './prog':

             10.48 msec task-clock                #    0.976 CPUs utilized
                 0      context-switches          #    0.000 K/sec
                 0      cpu-migrations            #    0.000 K/sec
               120      page-faults               #    0.011 M/sec
        43,086,088      cycles                    #    4.110 GHz
        99,345,603      instructions              #    2.31  insn per cycle
        11,580,757      branches                  # 1104.764 M/sec
            16,640      branch-misses             #    0.14% of all branches

       0.010739591 seconds time elapsed

       0.007173000 seconds user
       0.003586000 seconds sys


mike:2023_italian_cpp$
```

```
real    0m0.038s
user    0m0.037s
sys     0m0.001s
mike:2023_italian_cpp$ time ./prog
0.
1000001.
2000002.

real    0m0.014s
user    0m0.010s
sys     0m0.004s
mike:2023_italian_cpp$ time ./prog
0.
1000001.
2000002.

real    0m0.015s
user    0m0.011s
sys     0m0.004s
```

```
template<typename T>
struct VecN{
  // ========== Member Variables =====
  // Store indidividual components
  T* components;
  size_t mSize;

  // ========== Member Functions =====
  // Constructor
  VecN(size_t elements);
  // Print out the components
  void Print() const;
  // Add some components
  VecN<T>& operator+=(const VecN<T>& rhs);
};
```

Optimization Strategy/Pattern #4: **Specialization**

A compile-time and space versus run-time trade-off

Specializing functions

- So one optimization strategy we can use is to specialize functions or data structures
  - This means studying carefully a piece of code, finding the use case, and then determining that we can hand tune it to be faster.
    - And preferably do the tuning such that that our compiler cannot do better than us!
  - We're going to take advantage again of compile-time programming to specialize our code.

```
// generic addition overload
template<typename T, size_t length>
  VecN<T,length>& VecN<T,length>::operator+=(const VecN<T,length>& rhs){
  for(size_t i=0; i < length; ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Catch-all case generic case with no specialization

Specializing functions results

- First observe that we have added a template specialization avoiding a loop (i.e. getting into compiler optimization world)
  - This appears to have reduced overall time spent in operator+= shown below.

```
// generic addition overload
template<typename T, size_t length>
  VecN<T,length>& VecN<T,length>::operator+=(const VecN<T,length>& rhs){
    for(size_t i=0; i < length; ++i){
    components[i] += rhs.components[i];
  }
  return *this;
}
```

Catch-all case

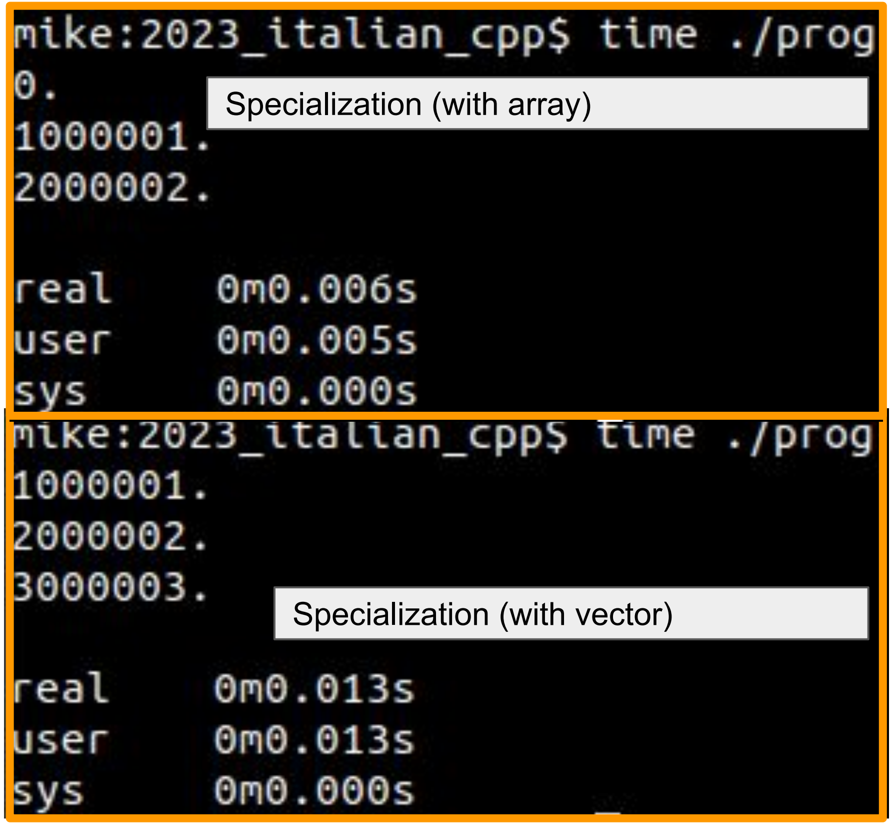
```
// Add a specialization with '3' integers
template<>
VecN<int,3>& VecN<int,3>::operator+=(const VecN<int,3>& rhs){
  components[0] += rhs.components[0];
  components[1] += rhs.components[1];
  components[2] += rhs.components[2];

  return *this;
}
```

***NEW*Specialization**

```
Samples: 46  of event 'cycles', Event count (approx.): 51376970
Overhead  Command  Shared Object       Symbol
  46.29%  prog     prog                [.] VecN<int, 3ul>::operator+=
  22.79%  prog     prog                [.] std::vector<int, std::allocator<int> >::operator[]
  13.78%  prog     prog                [.] std::vector<int, std::allocator<int> >::operator[]
   5.94%  prog     prog                [.] main
   5.68%  prog     ld-2.27.so          [.] do_lookup_x
   3.27%  prog     [kernel.kallsyms]   [k] task_work_run
   2.01%  prog     [kernel.kallsyms]   [k] unmap_page_range
   0.22%  prog     [kernel.kallsyms]   [k] perf_output_begin
   0.01%  perf     [kernel.kallsyms]   [k] native_sched_clock
   0.00%  perf     [kernel.kallsyms]   [k] native_write_msr
```

Specializing functions results

- From a performance standpoint, I got relatively good results
  - Perhaps our code layout has changed enough that we're not always optimized however!
  - Perhaps on a larger data structure, specialization can be more impactful -- and perhap enable other optimizations!
    - We may have even enabled specializations like this for SIMD to get further performance.



Optimization Strategy/Pattern #5: **Multi-phase initialization**

A space versus time trade-off affecting readability/maintenance

Multistage setup

- Consider the example to the right where we decide we want to use std::vector again as our underlying container
  - Often times we have data structures (including vectors) where it might be beneficial to setup the data structure in multiple stages.
    - i.e. reserve memory first, then setup components
- Note: For this particular pattern -- we probably need to increase length to something larger to be more meaningful in the results.

```cpp
// Constructor
template<typename T, size_t length>
  VecN<T,length>::VecN(){
  // Initialize components
  // in multiple steps
  components.resize(length); // allocate and fill
  for(size_t i =0; i < length; ++i){
    components[i] = i;
  }

  // Initialize components growing our vector slowly
  for(size_t i =0; i < length; ++i){
    components.push_back(i);
  }

}
```

Wrapping up VecN Example

Wrapping up VecN Example

- We’ve played around with a data structure thinking about 5 optimization strategies
  - Caching
  - Compile-Time Computation
  - Specialization
  - Solve the right problem with the right data structure
  - Multi-phase initialization
- We have also learned how we might investigate if our program is actually running faster
  - There exist more strategies however that I’d like to share briefly -- and may be discussed in future talks

More Patterns/Strategies

Hinting

- Hint on insertion
- Nice example on cppreference showing how ‘hints’ can be used for speeding up insertion in maps
  - https://en.cppreference.com/w/cpp/container/map/emplace_hint
- Consider another example of a list like data structure where we can ‘skip’ through it for faster insertion/traversals/searches [e.g. skip list

```cpp
int main() {
    std::cout << std::fixed << std::setprecision(2);
    timeit(map_emplace); // stack warmup
    timeit(map_emplace, "plain emplace");
    timeit(map_emplace_hint, "emplace with correct hint");
    timeit(map_emplace_hint_wrong, "emplace with wrong hint");
    timeit(map_emplace_hint_corrected, "corrected emplace");
    timeit(map_emplace_hint_closest, "emplace using returned iterator");
}
```

Possible output:

```
22.64  ms for plain emplace
 8.81  ms for emplace with correct hint
22.27  ms for emplace with wrong hint
 7.76  ms for corrected emplace
 8.30  ms for emplace using returned iterator
```

Precomputation

- C++ Compiler optimizations may do some of this
  - Common subexpression elimination
- Templates are our tool for doing work at compile-time
- C++11 and beyond has constexpr
  - You should try to constexpr as many things as possible.

Lazy versus Eager Evaluation

- Eager evaluation is evaluating the result immediately
- Lazy Computation is to delay our computation
  - std::async with std::launch::deferred
  - Multiple part construction of our objects as needed
- Copy-on-Write (COW)
- Consider ‘short-circuit evaluation’ as another way to avoid work that does not need to be done when ordering conditionals

Batching

- Consider in some domains like computer graphics, you want to 'batch' all of the draw calls together
  - (Either through instancing or some other mechanism)
- More simply -- buffered output is an example of this optimization

https://learnopengl.com/Advanced-OpenGL/Instancing

hashing

- Consider that we may want to take some long value (e.g. a long string) and compute a hash to an integer to reference the object by or otherwise compare two larger pieces of data.

Anecdote

- Performance is Tricky!
- I have heard on numerous occasions adding a random ‘printf’ to change the address layout has improved performance by 10+% before.
  - This is in the ‘lore’ in optimization, I first heard about at PLDI at 2013
  - Here’s a stack overflow post, and there exist possibly other notes
    - https://stackoverflow.com/questions/42358211/adding-a-print-statement-speeds-up-code-by-an-order-of-magnitude

And that's all folks!

- Optimization is fun, and it comes with many trade-offs
  - It's better to say there are 'strategies' versus 'patterns' -- the reality is we have lots of strategies to choose from versus cookie cooker solutions, and optimizing is often very iterative.
  - (Slides and code will be available for this talk)
- Make sure to go read the original Knuth paper so you can tell folks that you know the full quote! (i.e. optimization is not really the root of all evil) :)

Structured Programming with go to Statements

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A consideration of several different examples sheds new light on the problem of creating reliable, well-structured programs that behave efficiently. This study focuses largely on two issues: (a) improved syntax for iterations and error exits, making it possible to write a larger class of programs clearly and efficiently without **go to** statements; (b) a methodology of program design, beginning with readable and correct, but possibly inefficient programs that are systematically transformed if necessary into efficient and correct, but possibly less readable code. The discussion brings out opposing points of view about whether or not **go to** statements should be abolished; some merit is found on both sides of this question. Finally, an attempt is made to define the true nature of structured programming, and to recommend fruitful directions for further study.

Keywords and phrases: structured programming, **go to** statements, language design, event indicators, recursion, Boolean variables, iteration, optimization of programs, program transformations, program manipulation systems searching, Quicksort, efficiency

CR categories: 4.0, 4.10, 4.20, 5.20, 5.5, 6.1 (5.23, 5.24, 5.25, 5.27)

Italian C++ Community
++it
10 Years
JUNE 10 - ROME

Social: @MichaelShah
Web: mshah.io
Courses: courses.mshah.io
YouTube: www.youtube.com/c/MikeShah

Thank you Italian C++!

Optimization Design Patterns

12:15-13:05, Sat, 10th June 2023

50 minutes | Introductory Audience

Thank you!

Extras and Notes

Outline

- Introduction and when to optimize code
  - How to time your code
  - Brief discussion on timers and using a profiler
- Optimization Design Patterns Introduction
  - Design Time versus space tradeoffs
  - Patterns: Precomputation, lazy versus eager evaluation, batching, caching, specialization, hinting, hashing, and compiler optimization levels.
    - Each pattern will have 1 or more examples in Modern C++ with a quickbench (or equivalent) benchmark.
    - Will discuss the time versus space tradeoff (and in some cases the debuggability or lack of debuggability of the code.)
- Depending on allocated time slot, will discuss other possible patterns like how to choose the correct 'chunk' of data to look at, cache-aware algorithms, and where to look further.
- Conclusion: Summary of what was discussed and how to measure.