Qminers®

Digging Deep for Performance

Hloubkové dolování výkonu

Mgr. Petr Filipský

Agenda


DIGGING DEEP
FOR PERFORMANCE
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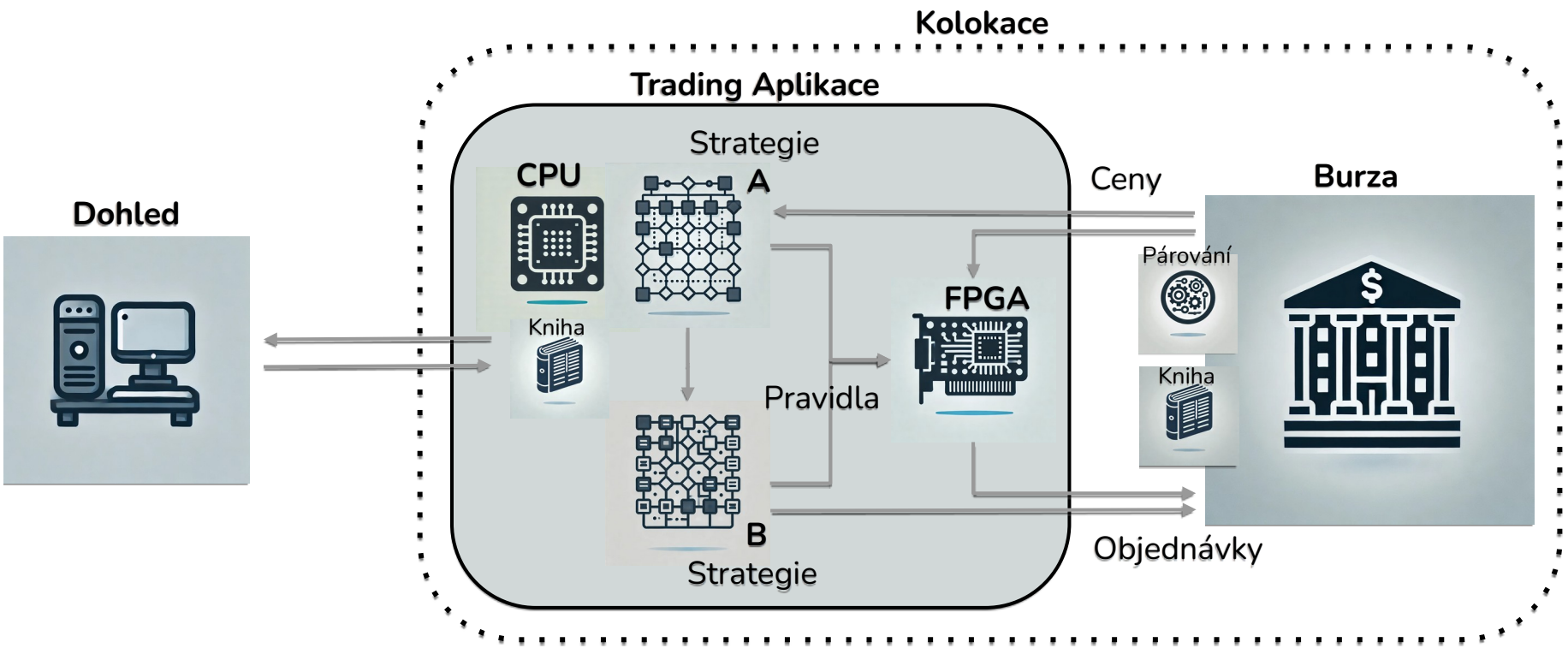
Agenda

- Qminers
  - Kdo jsme
  - Co vyvíjíme
  - V čem vyvíjíme
- Case studies (Pár případů z praxe)
  - Trocha teorie
  - Způsoby měření
  - Popis konkrétních situací
- Shrnutí

Motivation


Kolokace
Trading Aplikace
Strategie
CPU
A
Dohled
Ceny
Burza
Párování
FPGA
Kniha
Pravidla
Kniha
B
Objednávky
Strategie

Latency / Throughput / Bandwidth

Latency / Throughput / Bandwidth

- Minimalizace **Latence**
  - Extrémně důležitá v produkci (při samotném obchodování)
  - Reakce v řádu desítek mikrosekund
    (existují HW řešení v řádu stovek případně desítek ns)

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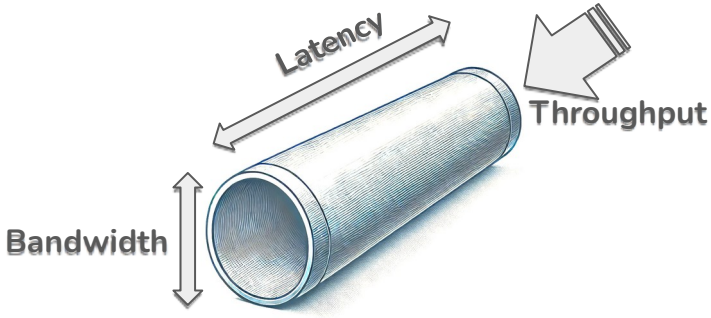
  - Duležitá např. při roční simulaci
  - Získání výsledků v řádu desítek minut



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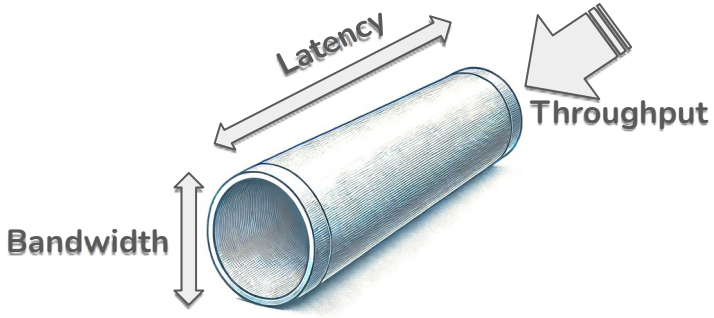
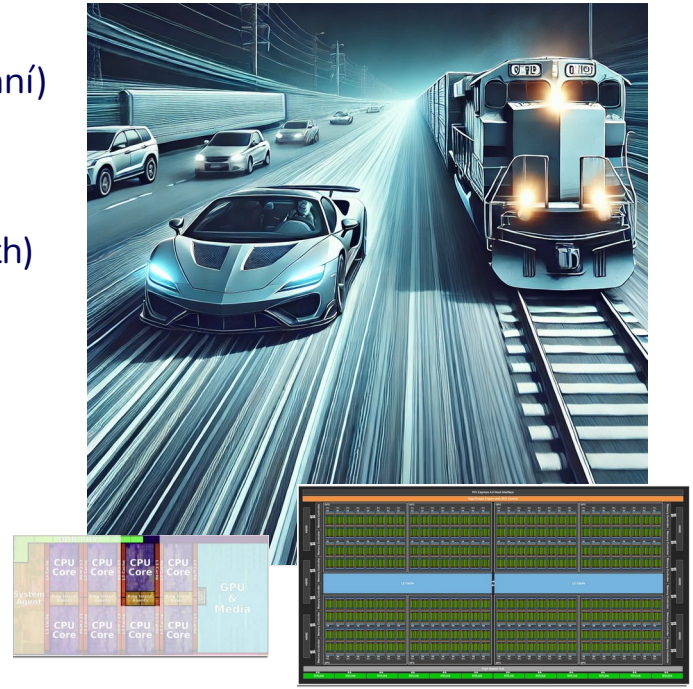
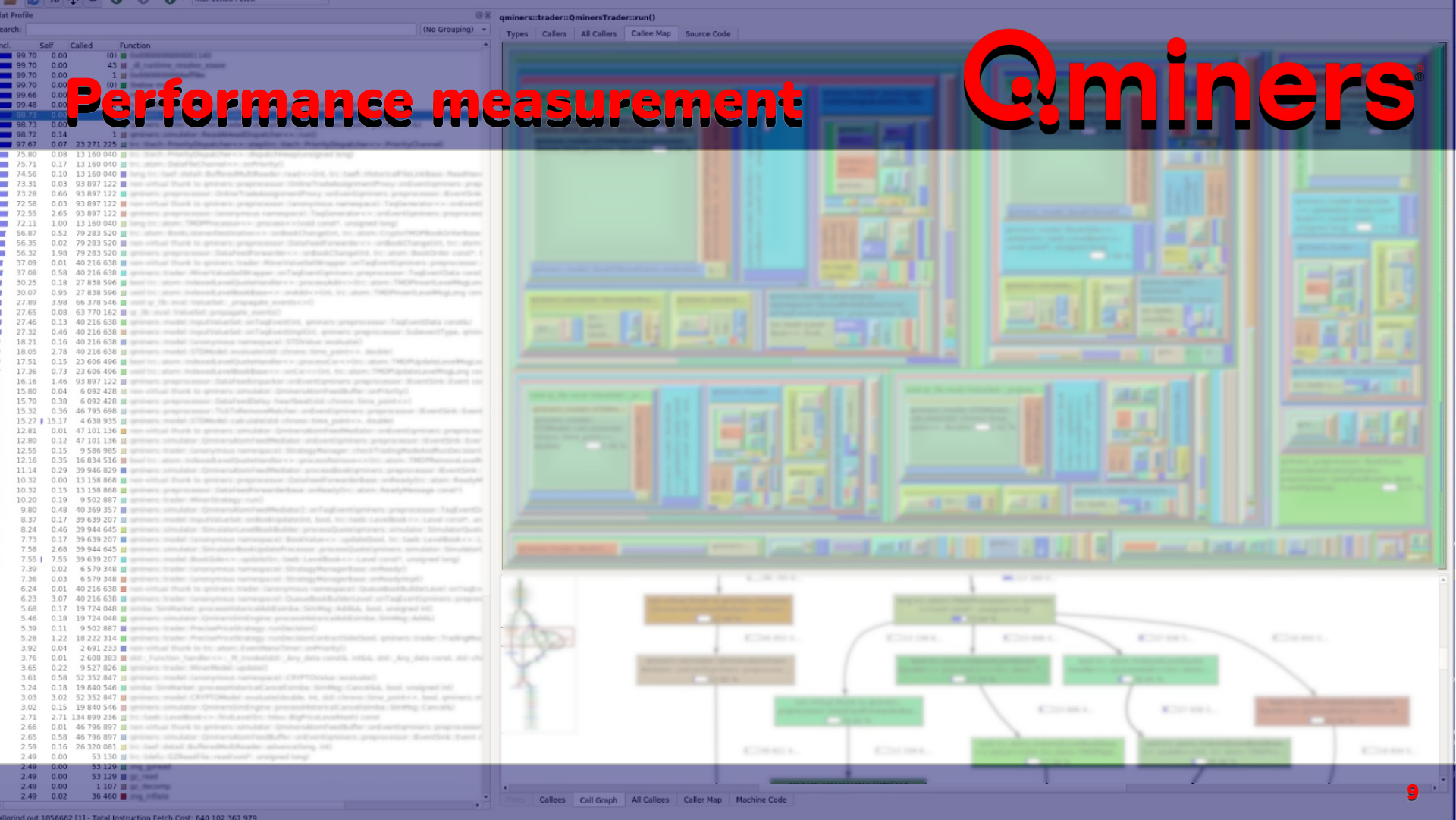




Performance measurement



Performance measurement

Samplování (Linux perf, Intel VTune, …)

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Instrumentace (Optick, ...)

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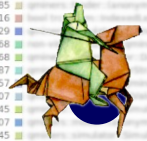

Emulace (Valgrind)

Performance measurement

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Samplování (Linux perf, Intel VTune, ...)

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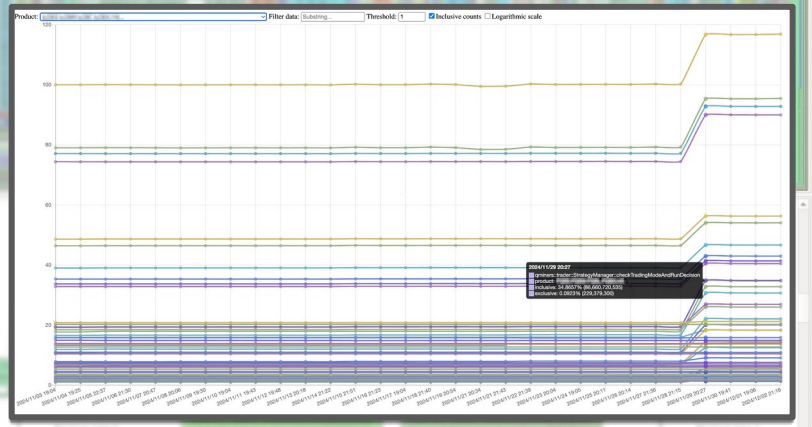
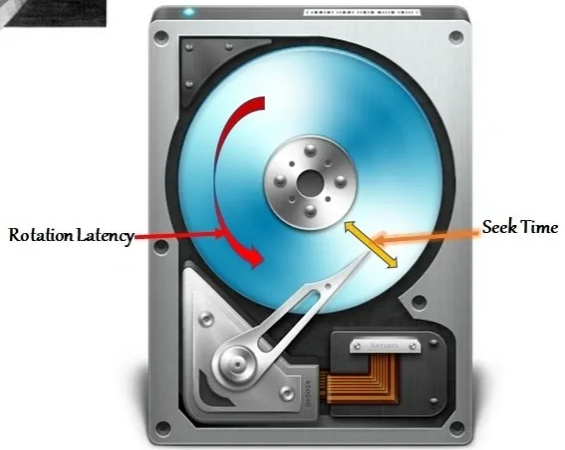
Emulace (Valgrind)



Memory

Memory

- Paměti s lineárním přístupem
  - Magnetické pásky
  - Plotnové disky



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  - Hierarchie vyrovnávacích pamětí
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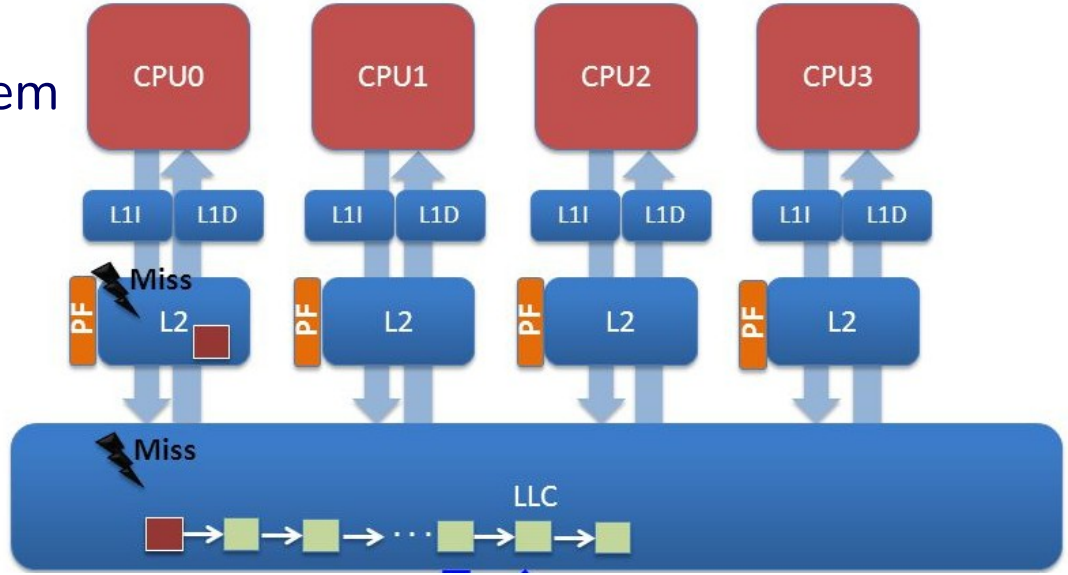

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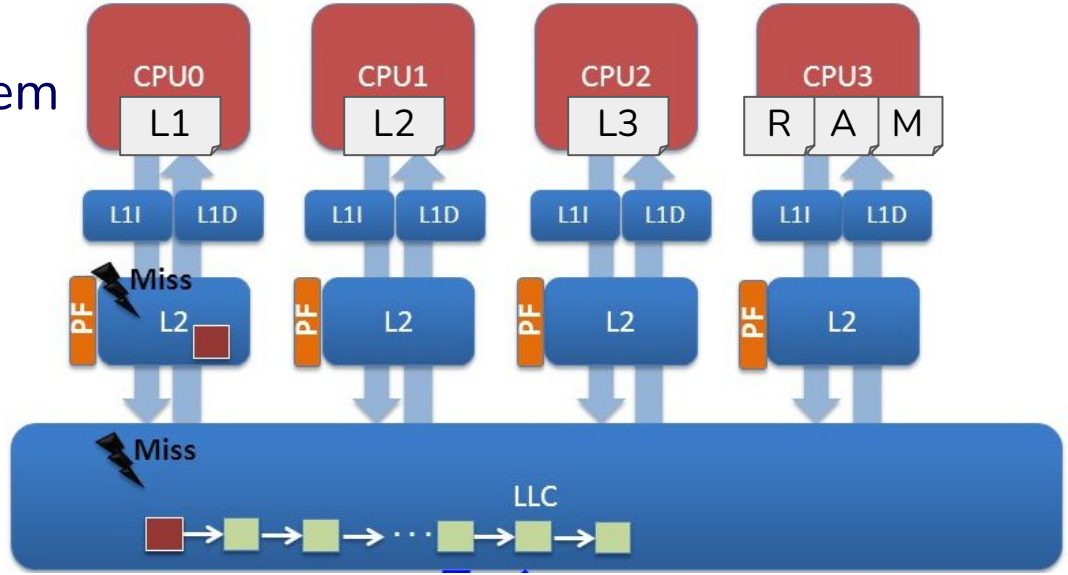

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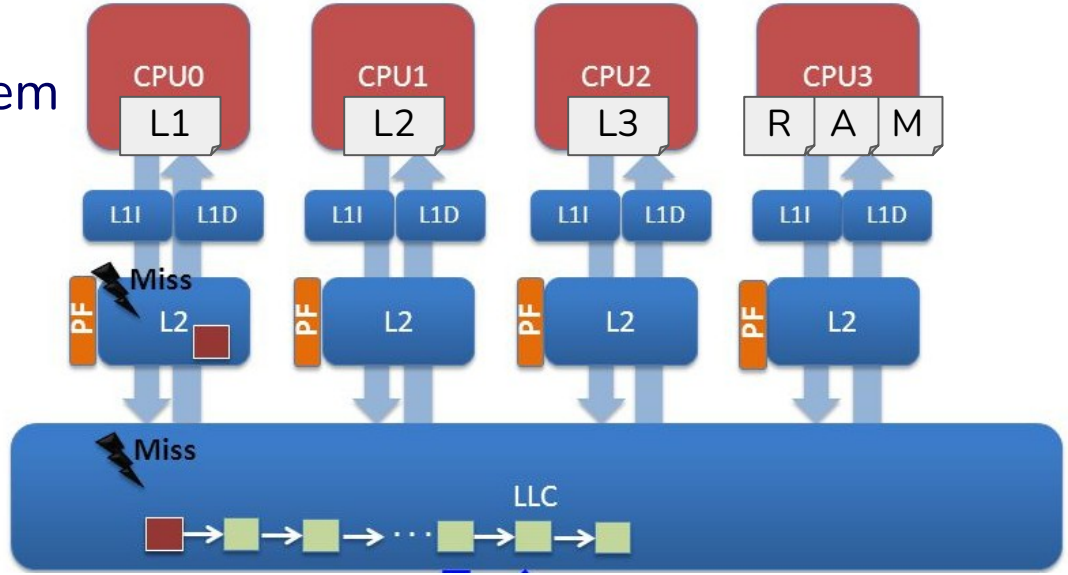

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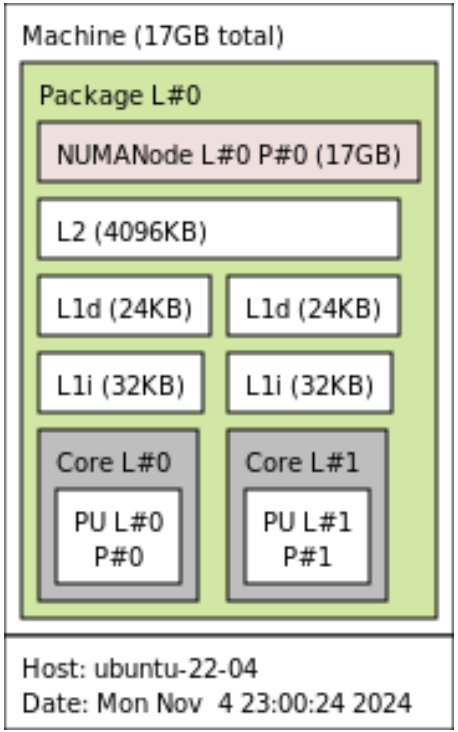

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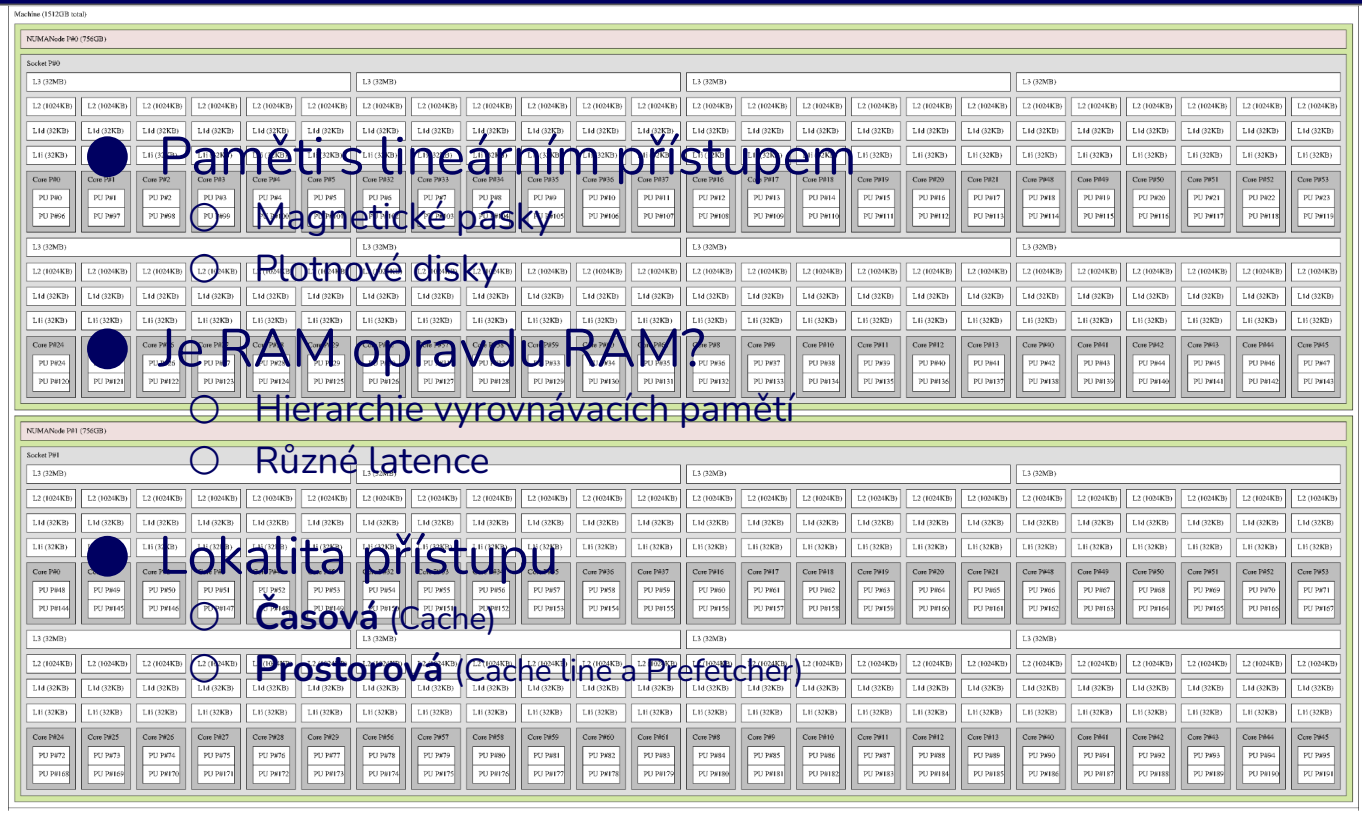

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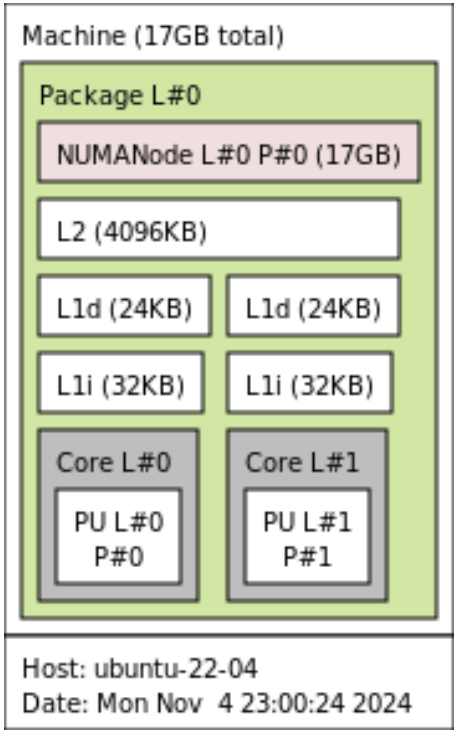

Data Oriented Design

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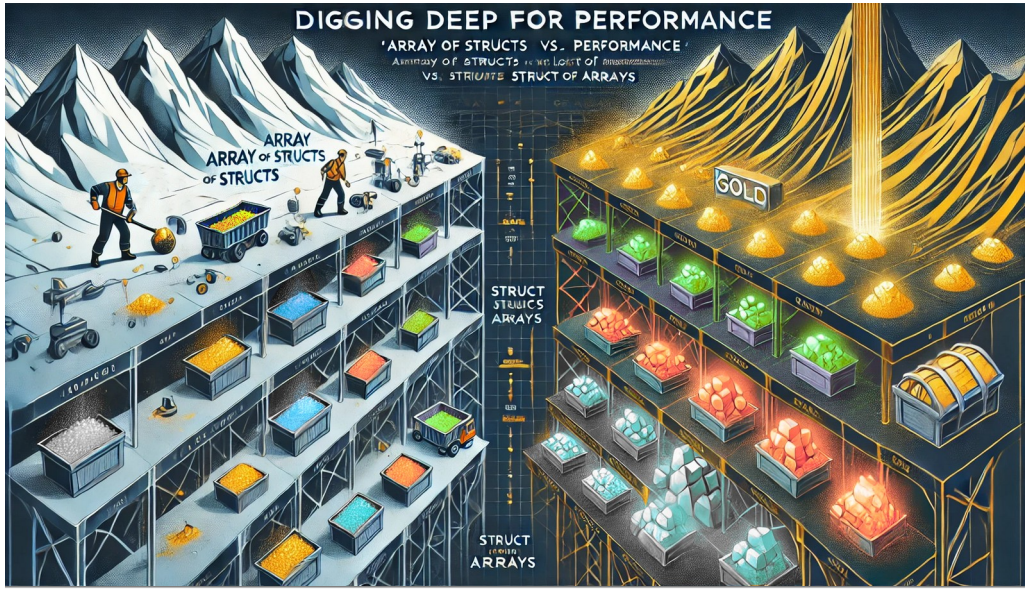
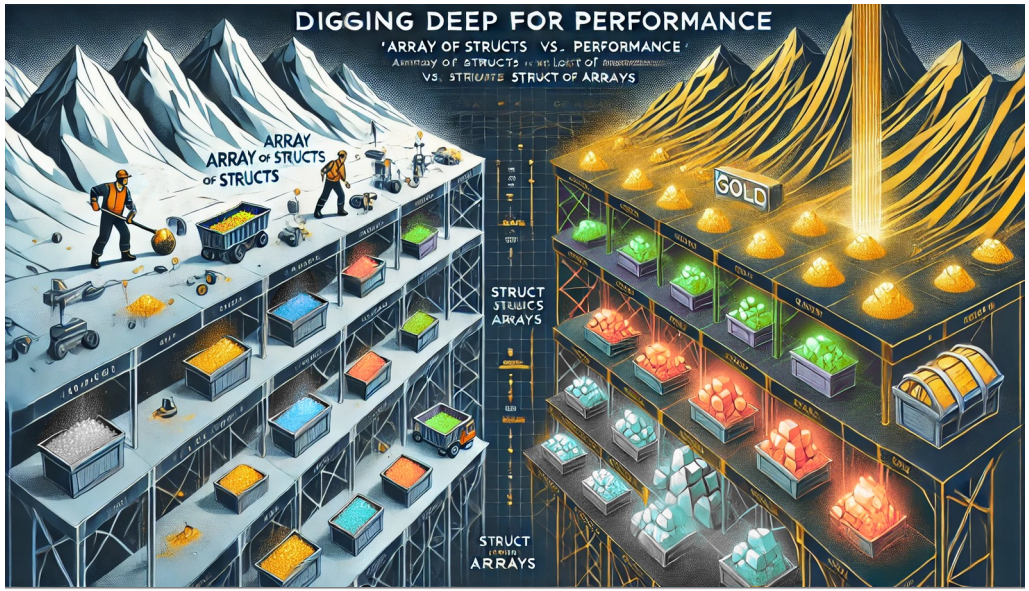


Data Oriented Design

- Array of Structs

```
namespace AOS {
struct Beast {
    Point3D pos{};
    Point3D vel{};
    HealthPoints hp{};
};
using Beasts = std::vector<Beast>;
```



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Data Oriented Design

Qminers

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- Struct of Arrays

```cpp
namespace SOA {
struct Beasts {
    explicit Beasts(size_t size)
      : pos(size), vel(size), hp(size) {
    }
    std::vector<Point3D> pos;
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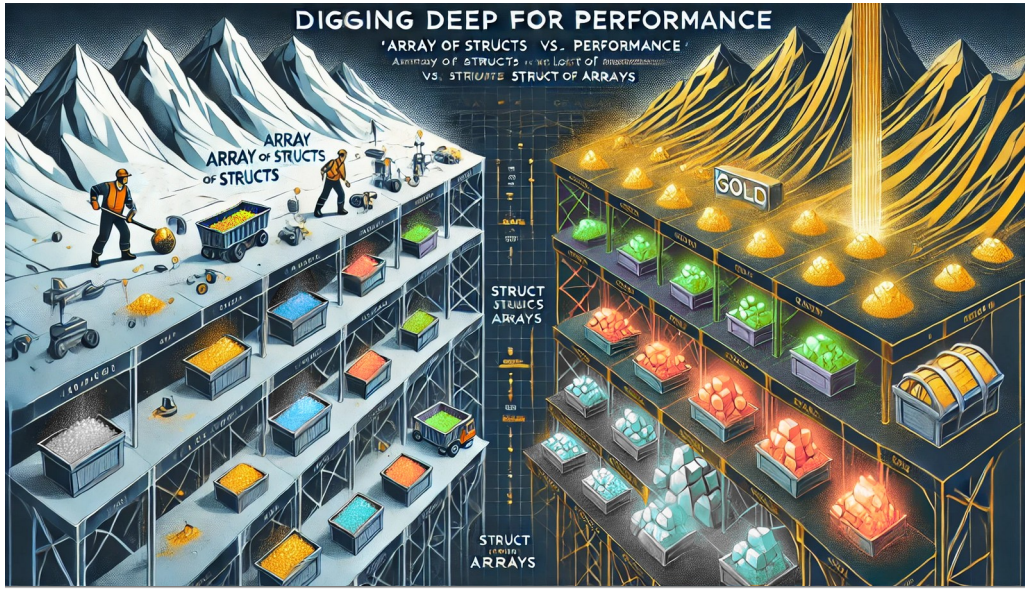

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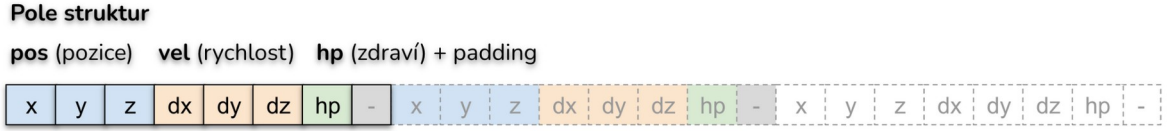

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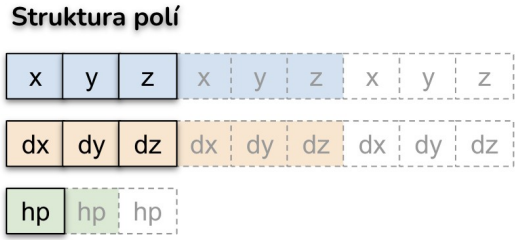

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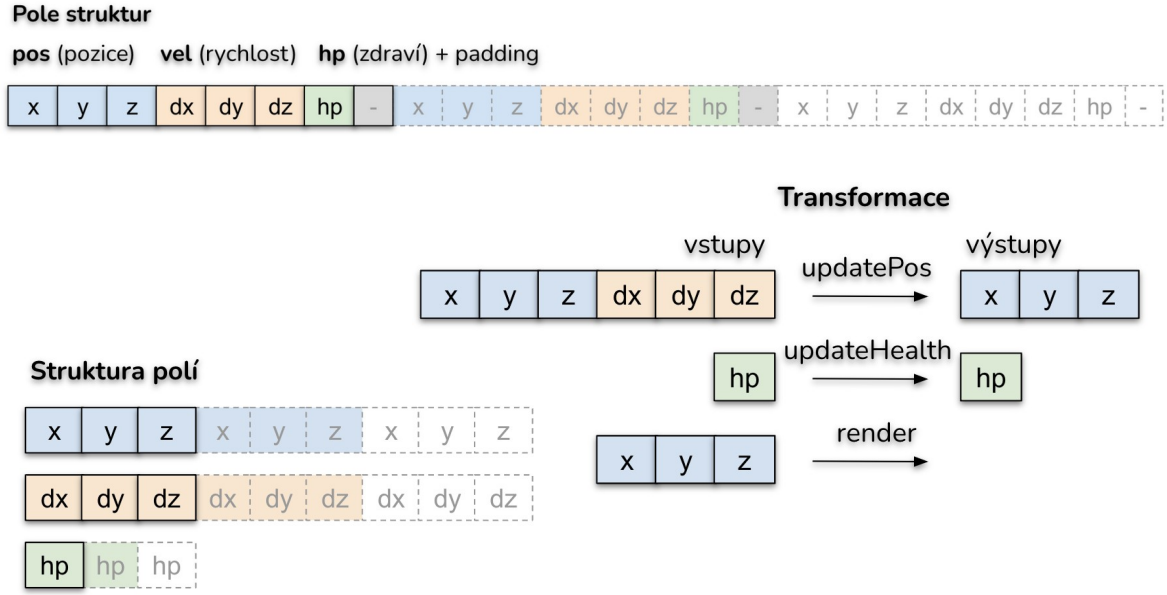

Godbolt example (QuickBench)

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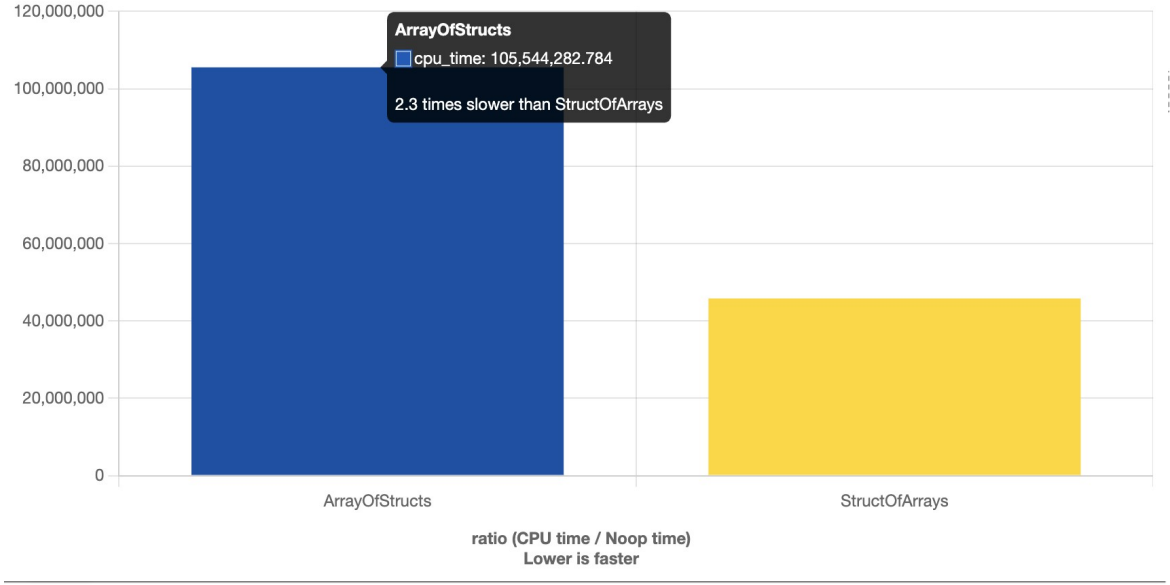

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CPU Pipeline

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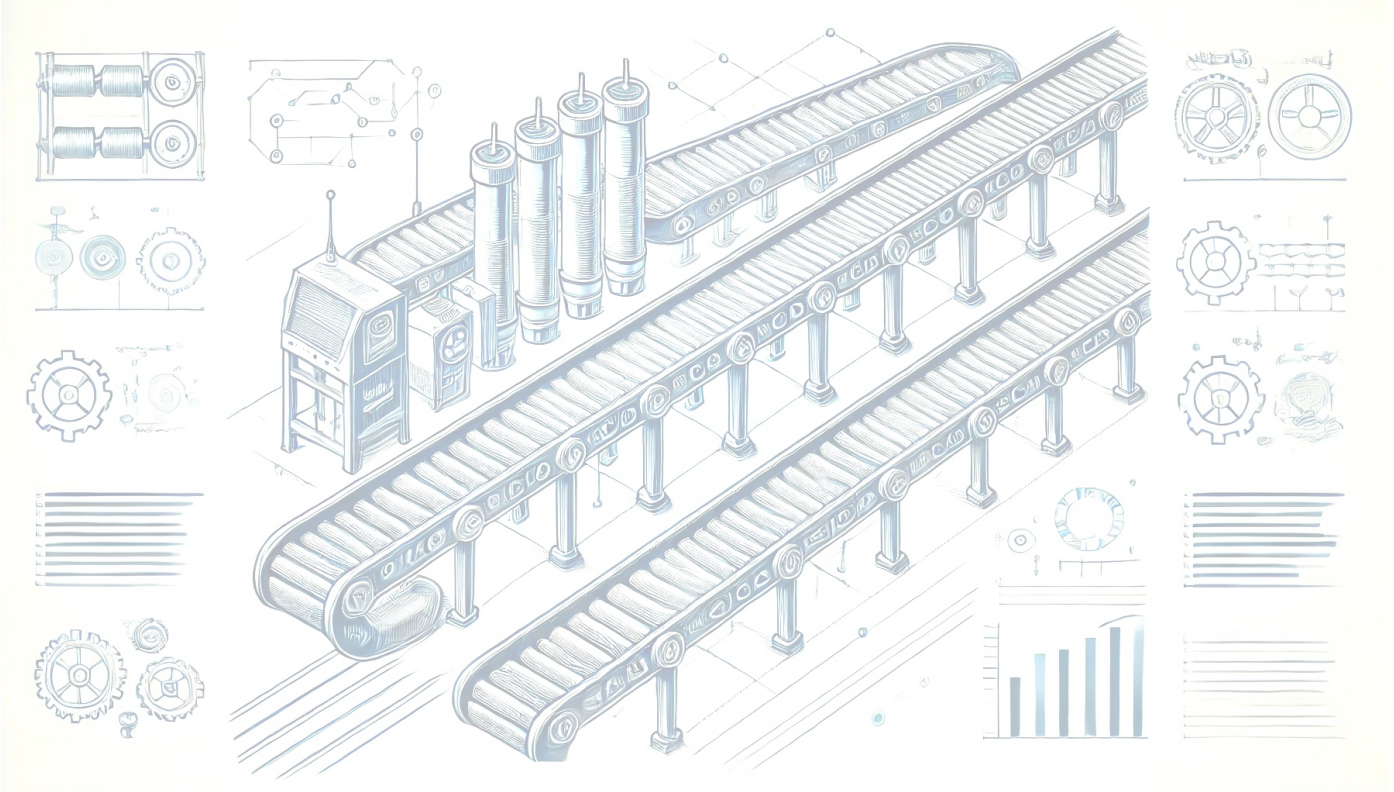
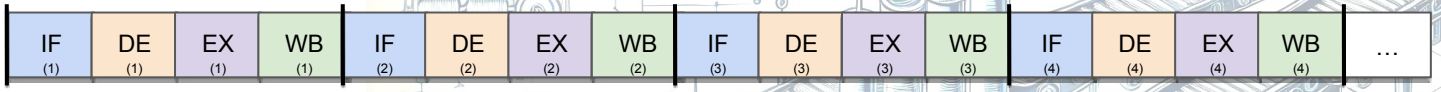


CPU Pipeline

- Sekvenční zpracování

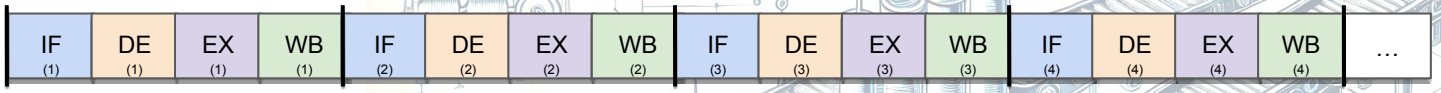


Credit: *Jobin Johnson - Branchless programming. Does it really matter?*

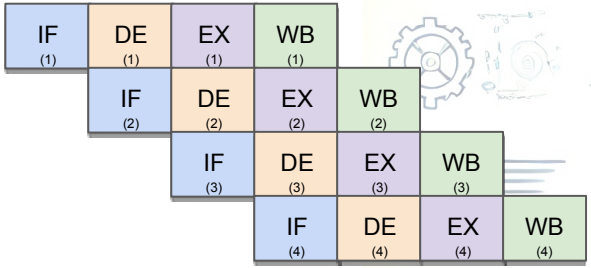
CPU Pipeline

Qminers

- Sekvenční zpracování



- Pipeline zpracování



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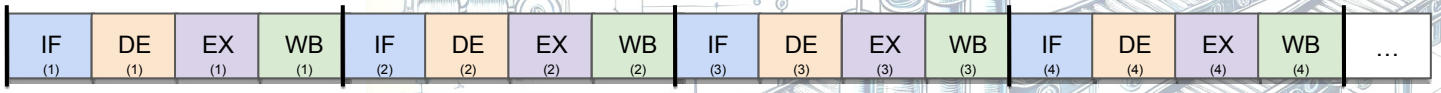
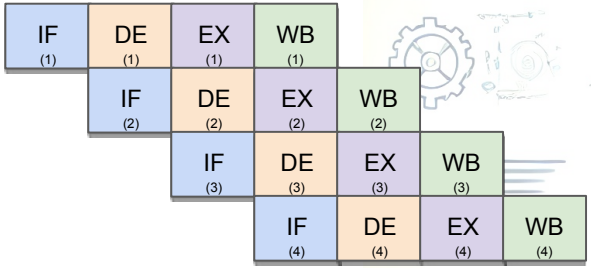
CPU Pipeline

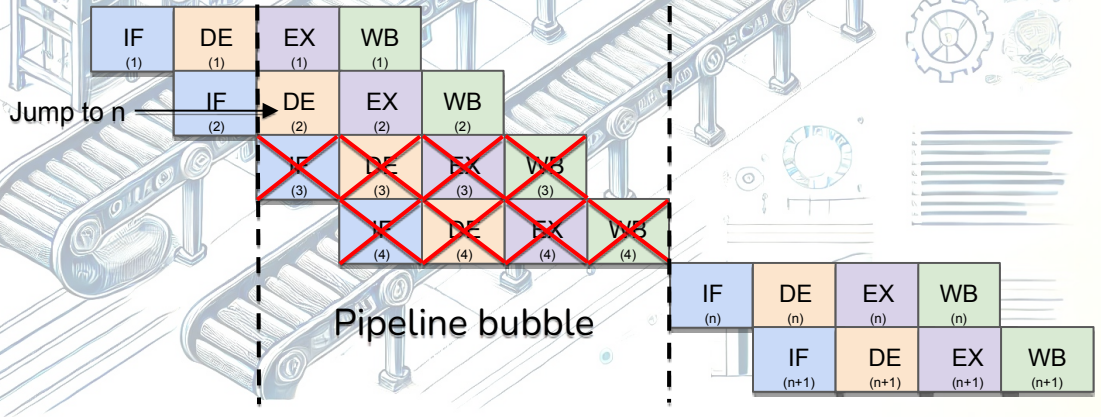
- **Sekvenční zpracování**



- **Pipeline zpracování**



- **Podmíněný skok** (nesprávně predikovaný)



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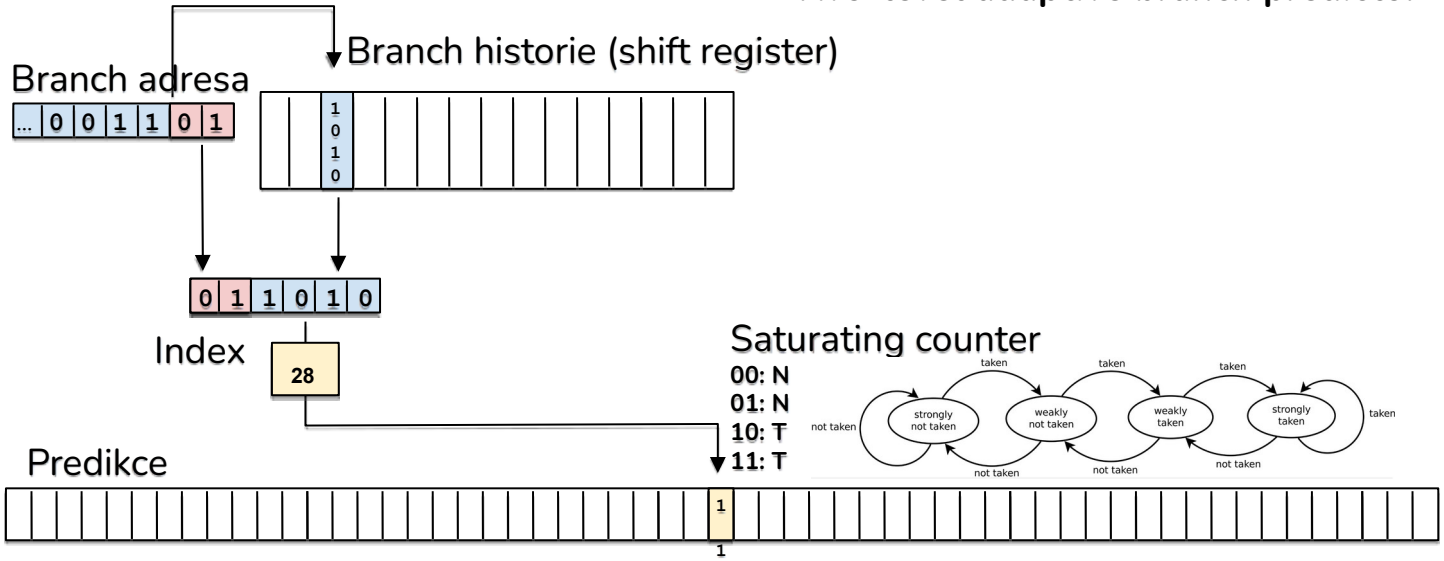
Branch Predictor

Branch Predictor

- Branch Predictor
  - Obvod v CPU, který předpovídá výsledky podmínek v kódu

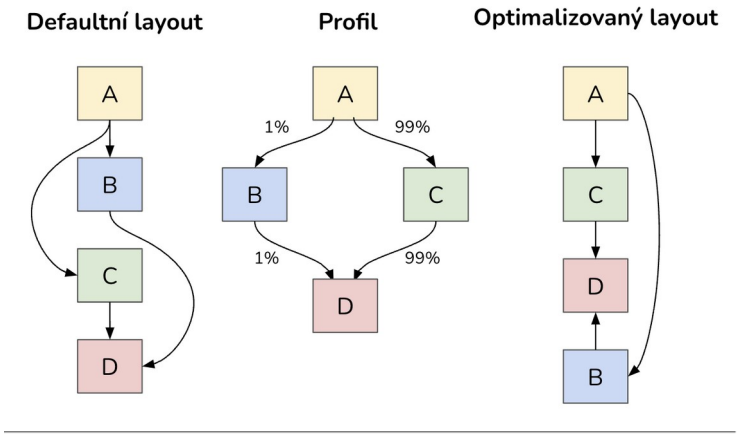
Two-level adaptive branch predictor



Credit: *Dan Luu - Branch prediction*

Branch Predictor

- Branch Predictor
  - Obvod v CPU, který předpovídá výsledky podmínek v kódu
- Profile-guided optimization
  - Optimalizace kódu na základě statistik získaných při běhu programu



Branch Predictor

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- Profile-guided optimization
  - Optimalizace kódu na základě statistik získaných při běhu programu
- Branch Latency

```
1. def handle_trade(trade):
2.     if trade.size > threshold:
3.         send_order_triggered_by_trade(trade)
```

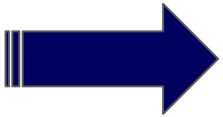
Branch Predictor

- Branch Predictor
  - Obvod v CPU, který předpovídá výsledky podmínek v kódu
- Profile-guided optimization
  - Optimalizace kódu na základě statistik získaných při běhu programu
- Branch Latency
  - CPU i překladače občas pracují “proti nám”
  - Řešením je použití specializovaného HW (FPGA, ...)

Branchless Programming

Branchless Programming

```
>>> def side_to_sign(isSell : bool) -> int:
...     return 1 if isSell else -1
...
>>> side_to_sign(True)
1
>>> side_to_sign(False)
-1
```



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Branchless Programming

Qminers

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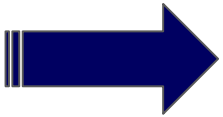

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...     return not isSell if multiplier >= 0.0 else isSell
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>>> get_side(-0.5, True)
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>>> get_side(0.5, True)
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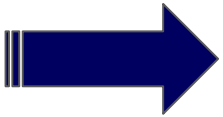

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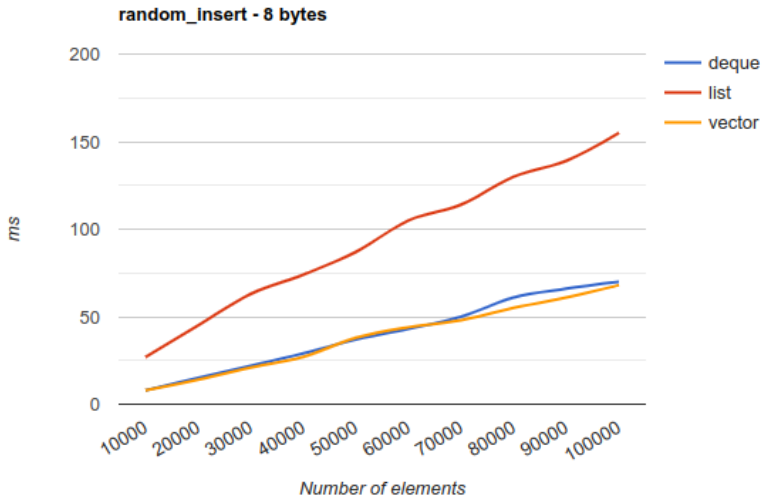
Godbolt example

Godbolt example (llvm-mca & flow-graph)

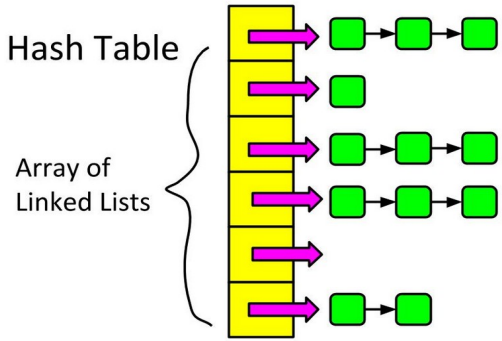
Data Structures

- Pole
  - Naprostá většina datových struktur



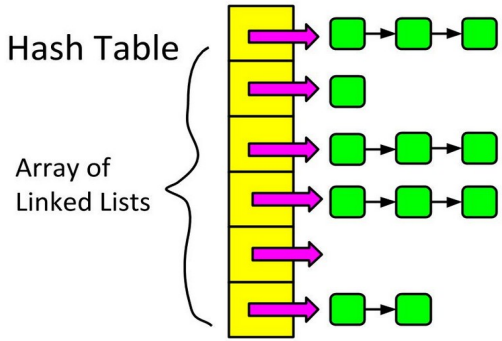
Data Structures

- Pole
  - Naprostá většina datových struktur
- Hashovací tabulky



Data Structures

- Pole
  - Naprostá většina datových struktur
- Hashovací tabulky
  - Např. kniha limitních objednávek



Linux perf (FlameGraph visualization)

Linux perf (FlameGraph visualization)

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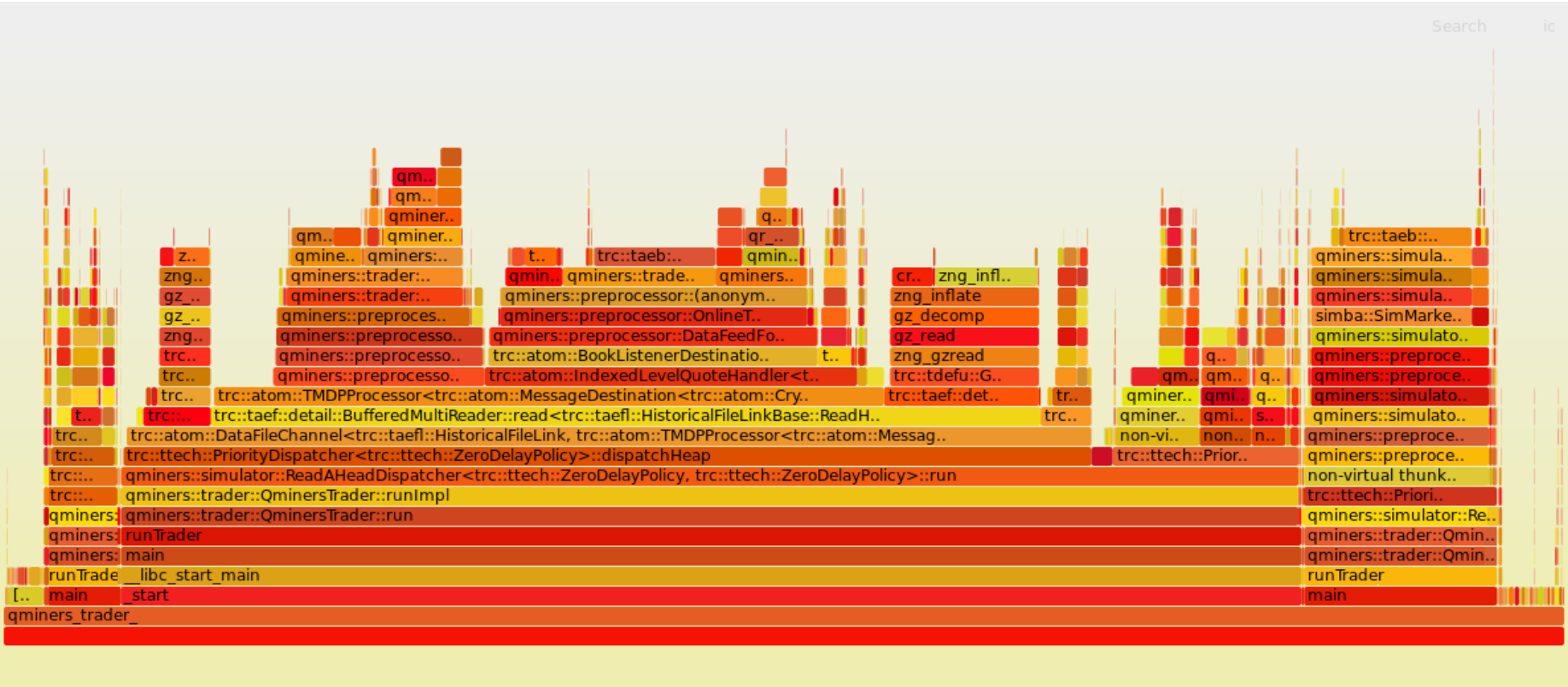

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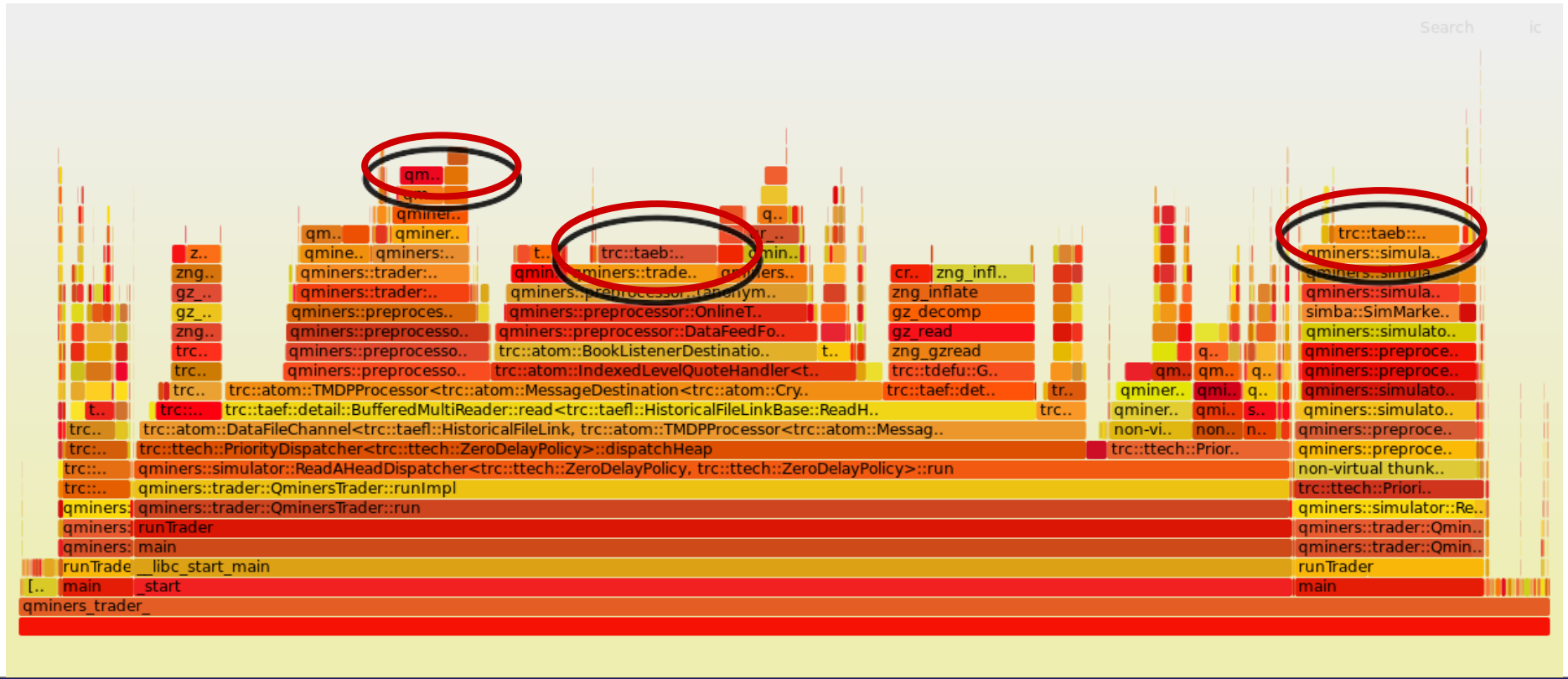

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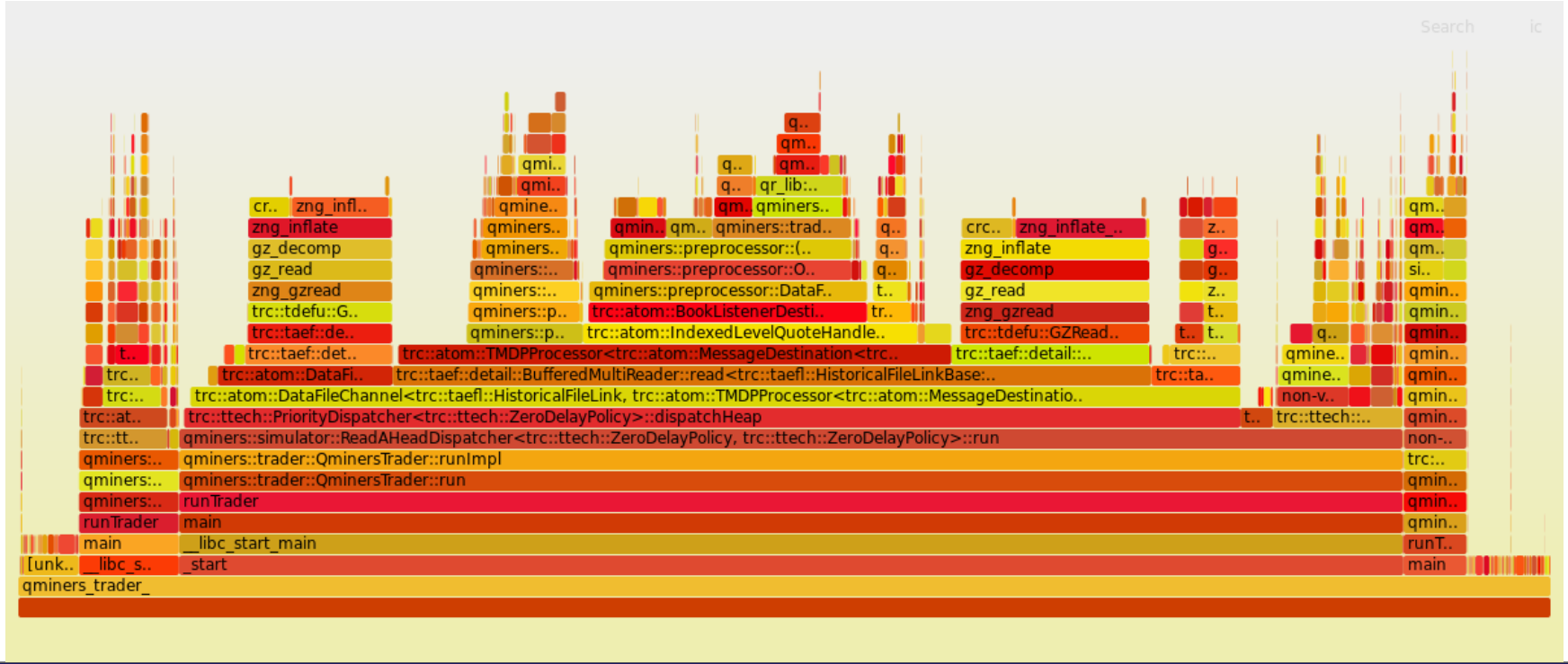
Qminers®



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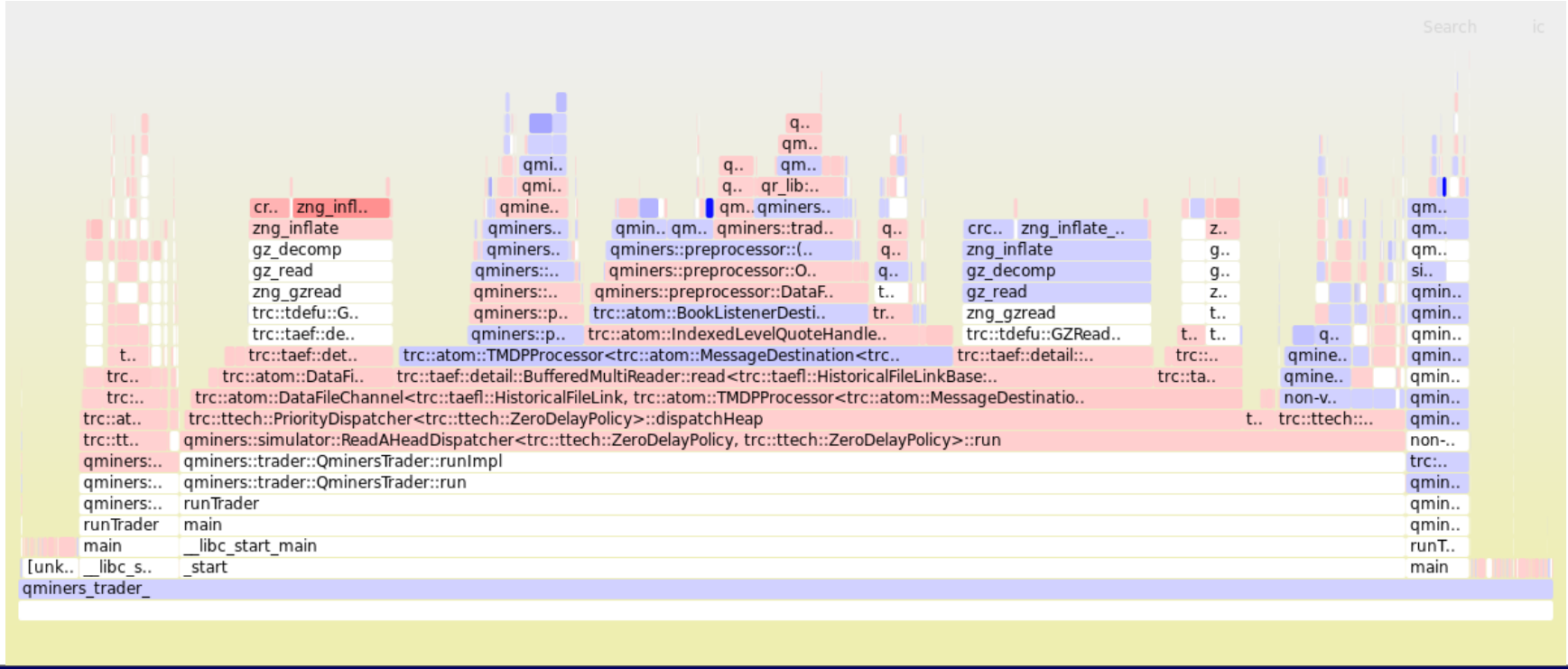
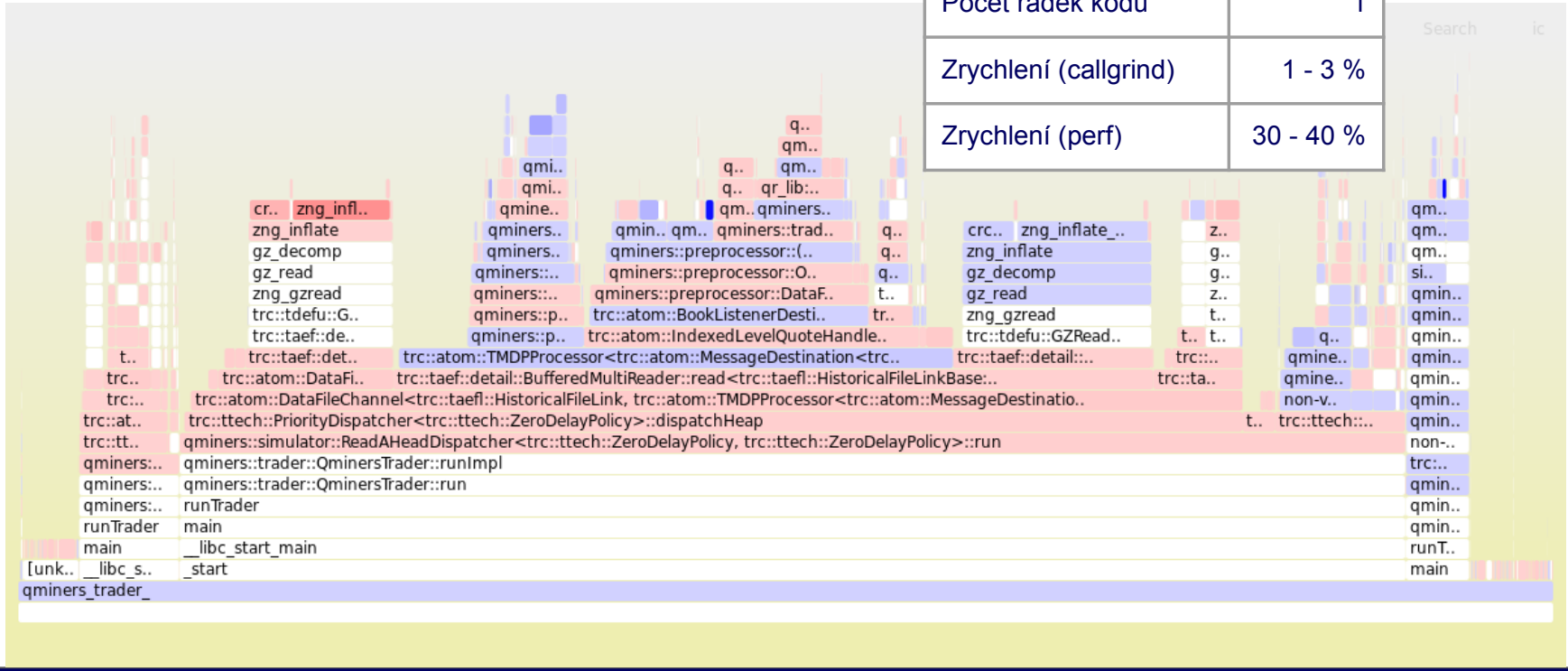
Qminers®



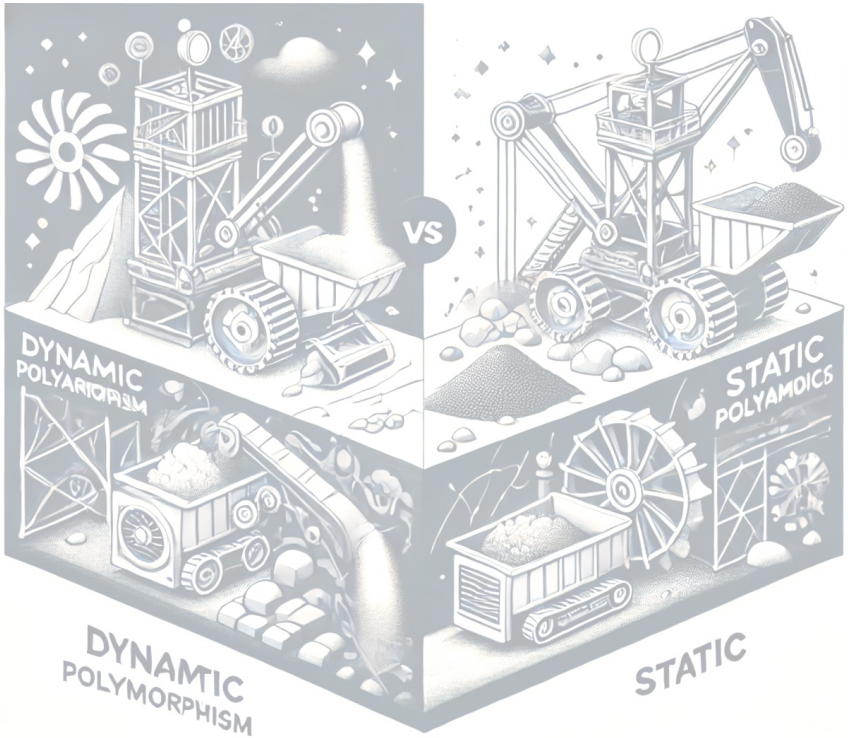
Linux perf (FlameGraph visualization)

Qminers®

Počet řádek kódu	1
Zrychlení (callgrind)	1 - 3 %
Zrychlení (perf)	30 - 40 %

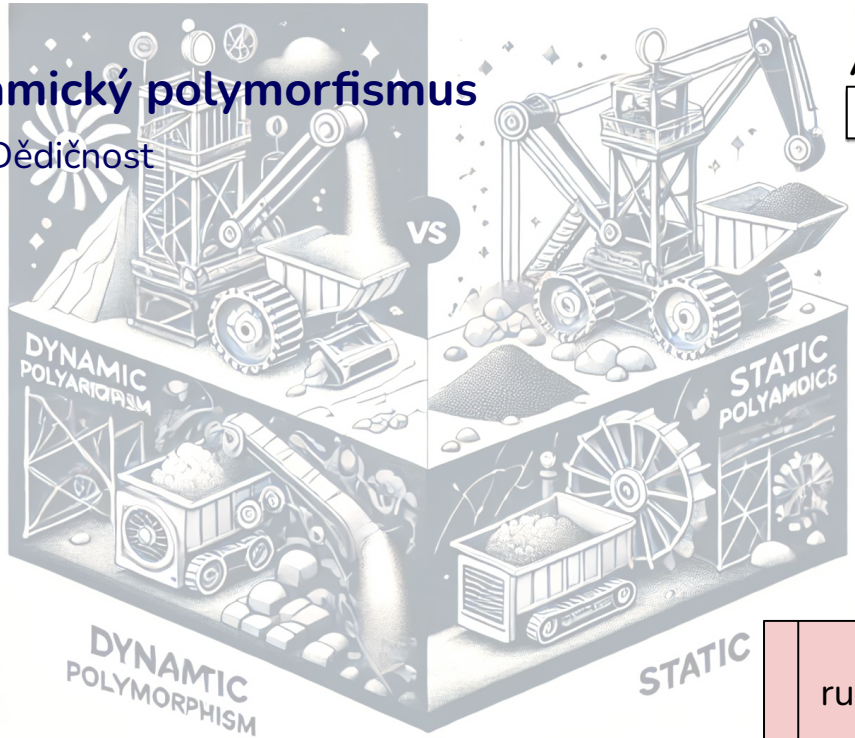


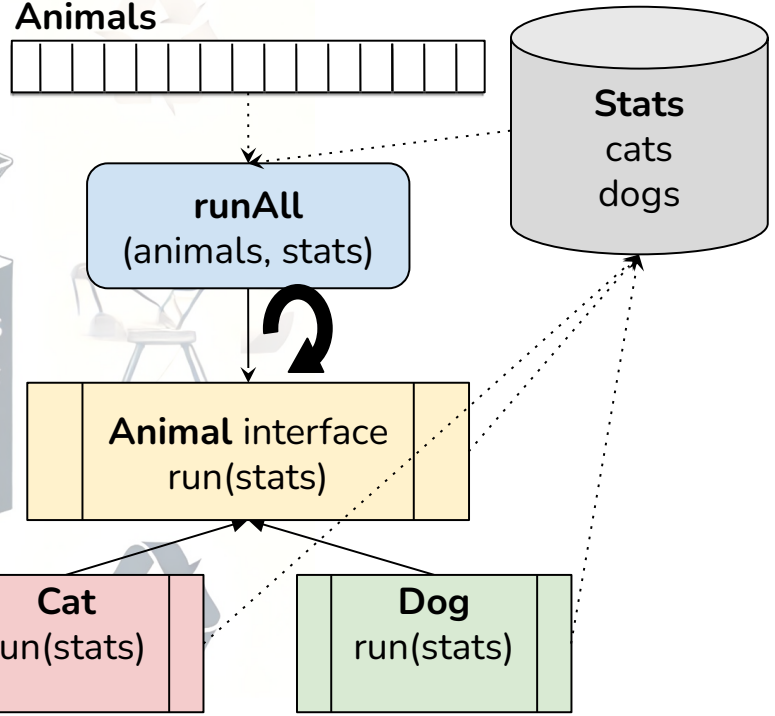
Dynamic / Static Polymorphism



Dynamic / Static Polymorphism

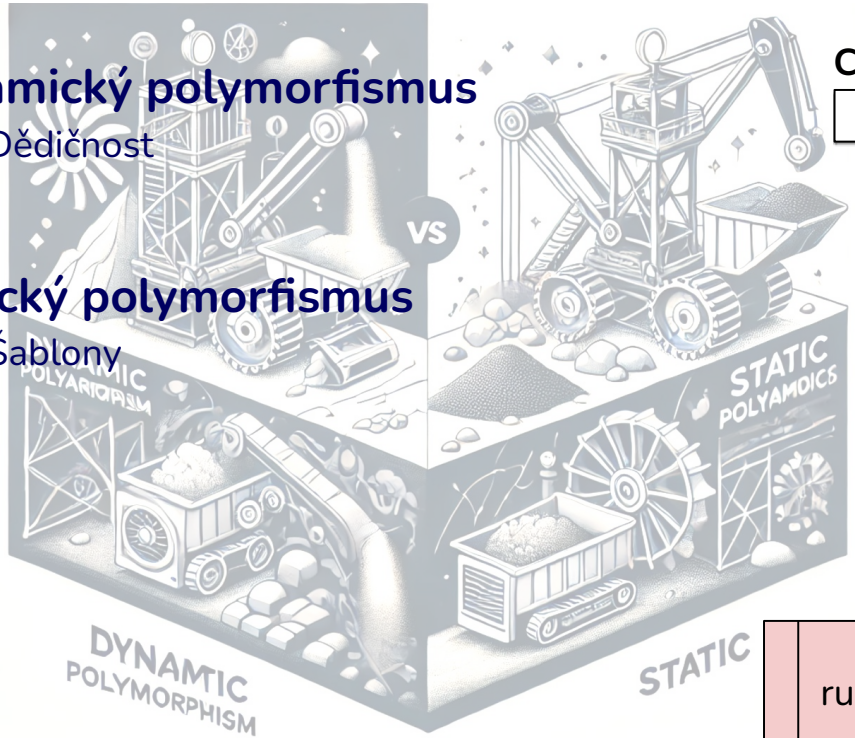
- Dynamický polymorfismus
  - Dědičnost

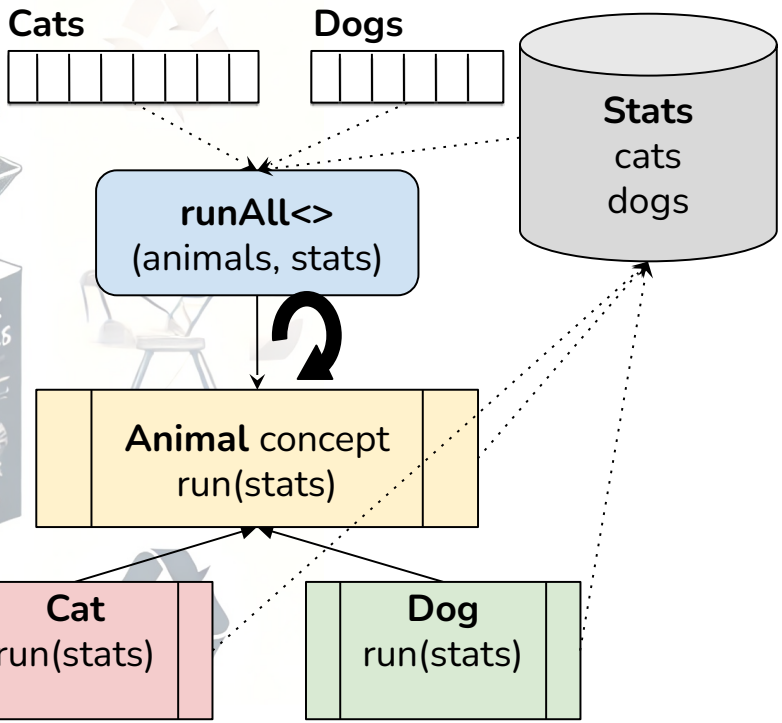




Dynamic / Static Polymorphism

- **Dynamický polymorfismus**
  - Dědičnost
- **Statický polymorfismus**
  - Šablony





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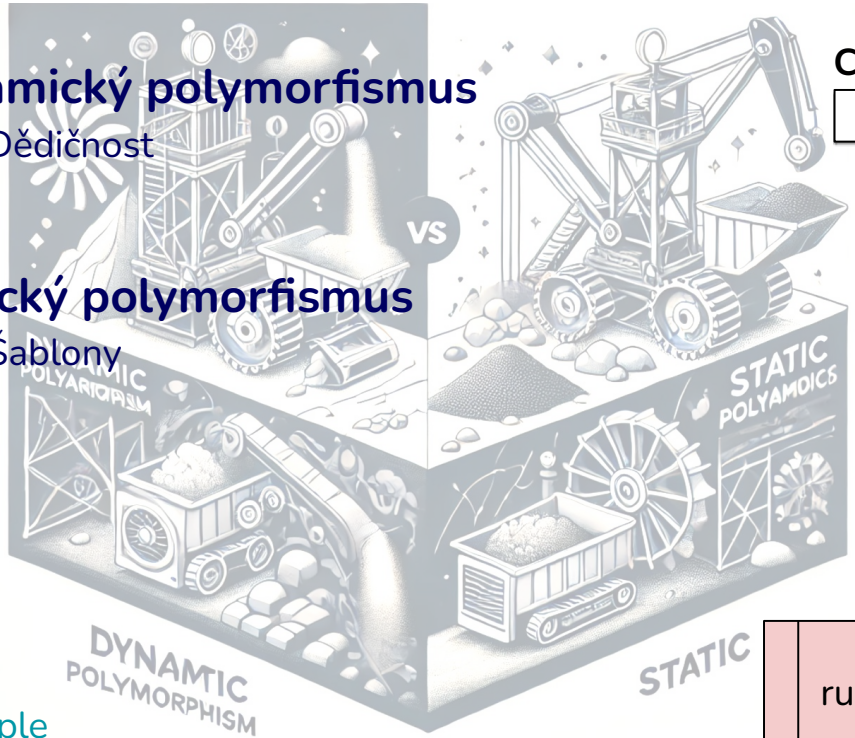

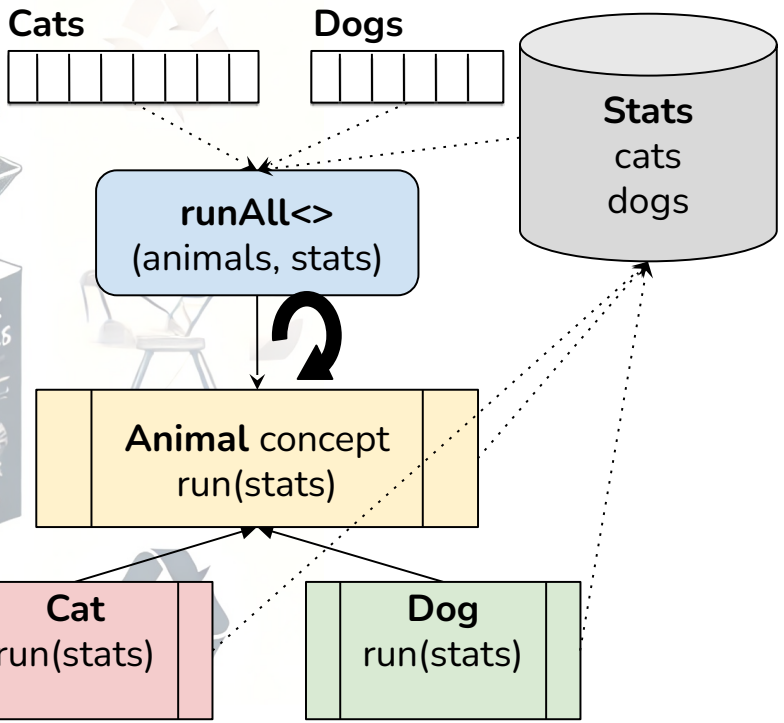

[Godbolt example]

Efficiency vs. Effectiveness

Efficiency vs. Effectiveness

- **Efficiency** - účinnost
  - Dosahujeme cílů s minimálním plýtváním zdroji?
  - Kolik prostředků potřebujeme k tomu, co děláme?
  - Používáme “the right tool for the job”?

Efficiency vs. Effectiveness

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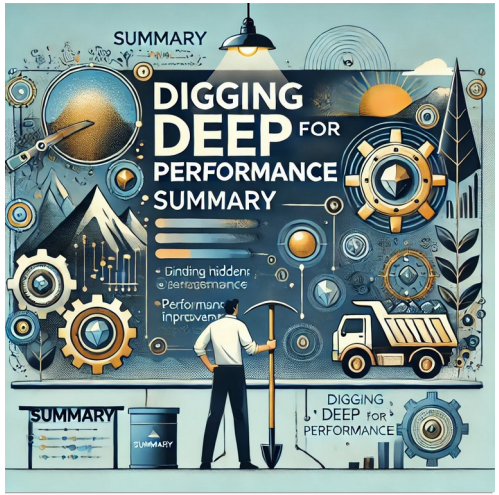
  - Kolik prostředků potřebujeme k tomu, co děláme?
  - Používáme “the right tool for the job”?

- **Effectiveness** - účelnost
  - Pracujeme na těch správných věcech?
  - Neděláme něco zbytečně složitě?
  - Opravdu vše, co děláme, plní svůj účel?

Summary


SUMMARY
DIGGING
DEEP FOR
PERFORMANCE
SUMMARY
SUMMARY
DIGGING
DEEP FOR
PERFORMANCE

Summary



- Vysvětlení pojmů na příkladech
  - Latence vs. Propustnost
  - Memory hierarchy a Data oriented design
  - Branch Predictor a Branchless programming
  - Dynamický vs. Statický Polymorfismus
  - Účinnost vs. Účelnost

- Složitosti dnešního HW … nelze spoléhat na …
  - … to, že CPU se bude chovat adekvátně pro váš use-case
  - … zastaralé poučky (*O(N)* lepší než *O(1)* s vysokým faktorem)
  - … optimalizace překladače (je třeba mít intuici, jak HW funguje)
  - … vlastní intuici (je třeba měřit)
  - … jeden druh měření (je třeba kombinovat různé techniky)

Links & Sources

- **Qminers** ... https://qminers.com

- **Videos**
  - Scott Meyers: Cpu Caches and Why You Care ... https://www.youtube.com/watch?v=WDIkqP4JbkE
  - Mike Acton: Data-Oriented Design and C++ ... https://www.youtube.com/watch?v=rX0ItVEVjHc
  - Matt Godbolt: Compiler Explorer 2023: What's New? ... https://www.youtube.com/watch?v=Ey0H79z_pco
  - Fedor Pikus: Branchless Programming in C++ ... https://www.youtube.com/watch?v=g-WPhYREFjk
  - Fedor Pikus: C++ Type Erasure Demystified ... https://www.youtube.com/watch?v=p-qaf6OS_f4
  - Mathieu Ropert: Data Oriented Design and ECS Explained ... https://www.youtube.com/watch?v=xm4AQj5PHT4
- **Tools**
  - Compiler explorer ... https://godbolt.org
  - Valgrind ... https://valgrind.org/
  - Linux perf ... https://perfwiki.github.io/main
  - Flamegraph visualization ... https://github.com/brendangregg/FlameGraph
  - Optick Profiler for games ... https://optick.dev/
  - Intel VTune Profiler ... https://www.intel.com/content/www/us/en/developer/tools/oneapi/vtune-profiler.html
- **Articles**
  - Dan Luu: Branch prediction ... https://danluu.com/branch-prediction/
  - Ulrich Drepper: What every programmer should know about memory ... https://people.freebsd.org/~lstewart/articles/cpumemory.pdf
  - Jobin Johnson: Branchless programming. Does it really matter? ... https://dev.to/jobinrjohnson/branchless-programming-does-it-really-matter-20j4
  - PACMan: Prefetch-Aware Cache Management for high performance caching ... https://ieeexplore.ieee.org/document/7851493
  - C++ Tutorial: Intro to Hash Tables ... https://pumpkinprogrammerdotcom4.wordpress.com/2014/06/21/c-tutorial-intro-to-hash-tables
  - C++ benchmark – std::vector vs. std::list vs. std::deque ... https://baptiste-wicht.com/posts/2012/12/cpp-benchmark-vector-list-deque.html
  - Xaktly - Determinant & Cramer's rule ... https://xaktly.com/MatrixDeterminant.html
  - Profile Guided Optimization (PGO) – Under the Hood ... https://devblogs.microsoft.com/cppblog/profile-guided-optimization-pgo-under-the-hood
  - Björn Fahller – Performance of flat maps ... https://playfulprogramming.blogspot.com/2017/08/performance-of-flat-maps.html

Source: ChatGPT

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Děkuji za pozornost

Bonus: Data Oriented Design

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- **Mapa jako pole**
  - Klíče jsou tříděné
  - Binární nebo sekvenční vyhledávání

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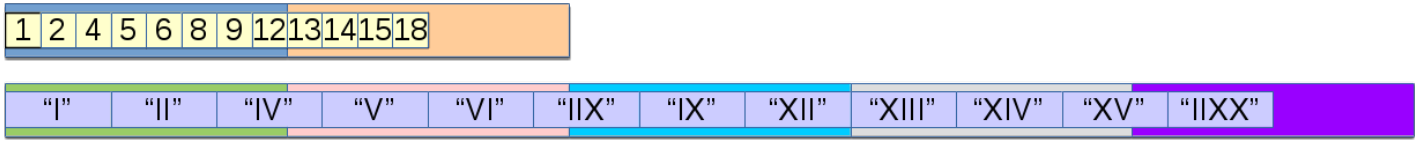
- **Pole párů**

Credit: *Björn Fahller – Performance of flat maps*

Bonus: Data Oriented Design

- Mapa jako pole
  - Klíče jsou tříděné
  - Binární nebo sekvenční vyhledávání
- Pole párů

- Dvě oddělená pole



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Bonus: Branch Prediction

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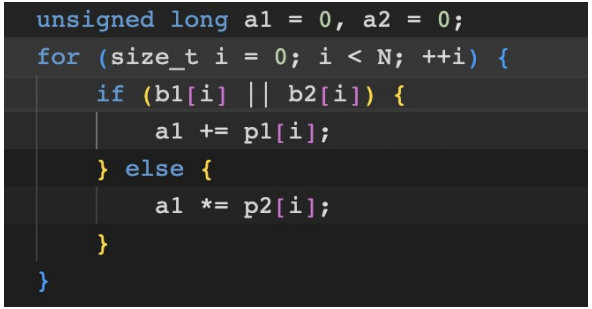

```
unsigned long a1 = 0, a2 = 0;
for (size_t i = 0; i < N; ++i) {
    if (b1[i] || b2[i]) {
        a1 += p1[i];
    } else {
        a1 *= p2[i];
    }
}
```

Godbolt example

(QuickBench)

Credit: *Fedor Pikus: Branchless Programming in C++*

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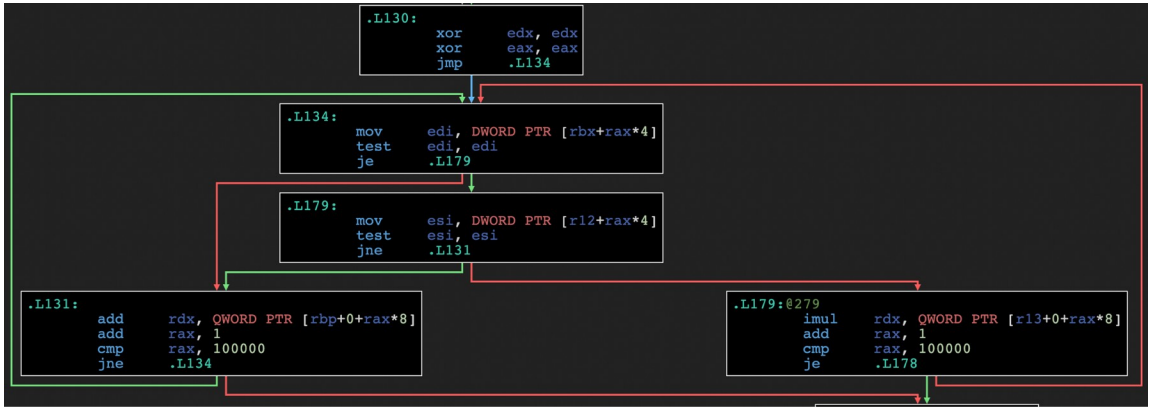

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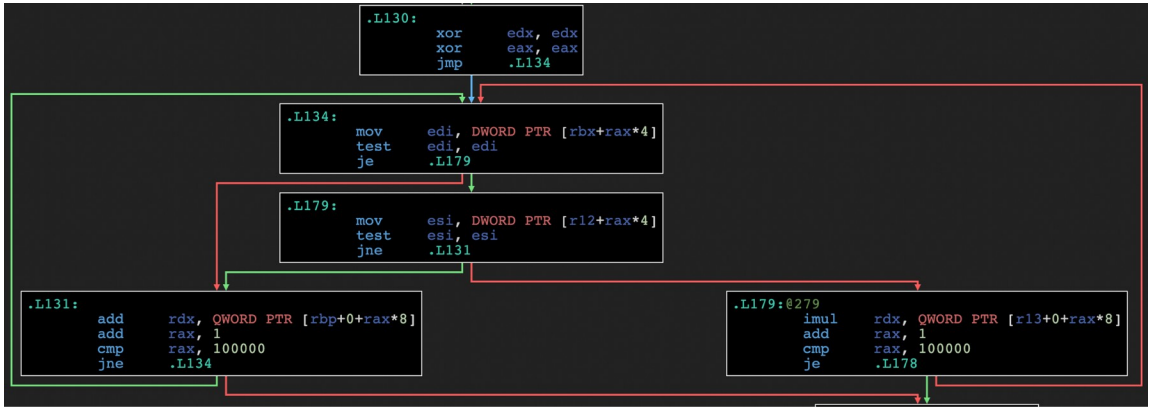


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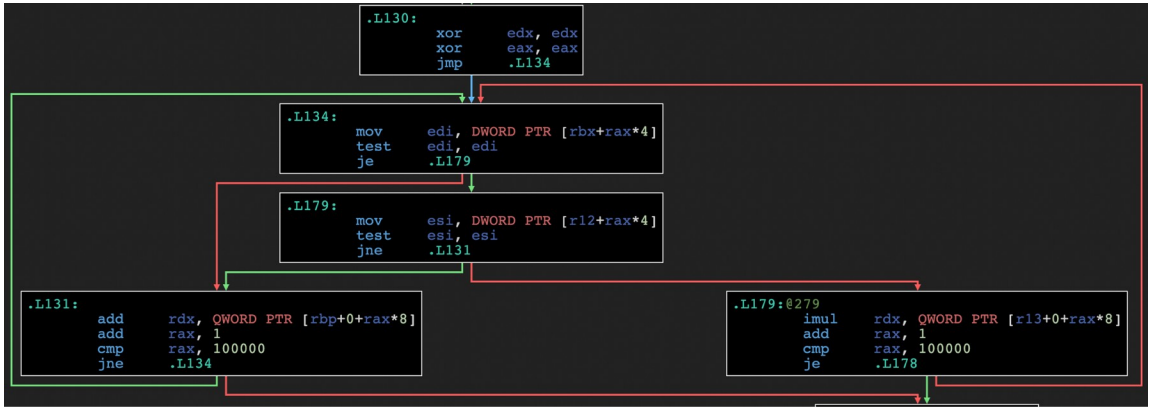
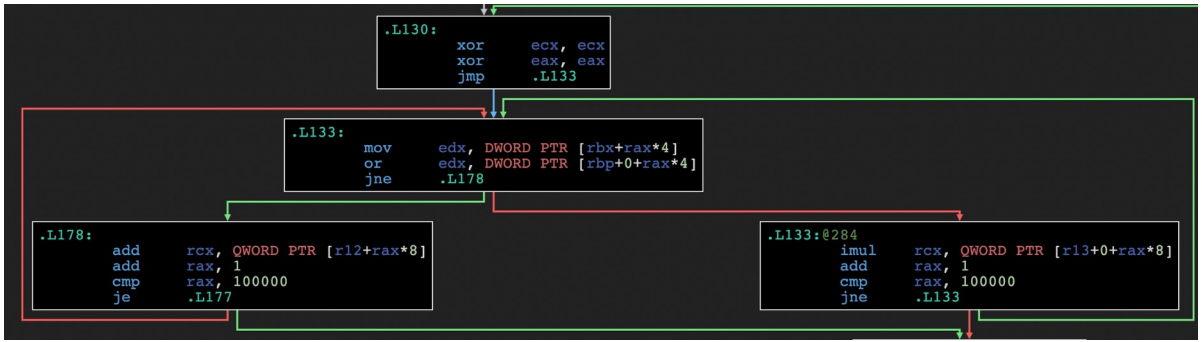




Credit: *Fedor Pikus: Branchless Programming in C++*

Bonus: Branch Prediction

Qminers

	Callgrind (#instr)	Perf (time)	Details
Logical OR	134,563,029	0.853 ms	
Bitwise OR	172,902,709	0.506 ms	

```
-----------------------------------------------------------------------------
Benchmark                   Time             CPU   Iterations UserCounters...
-----------------------------------------------------------------------------
BranchMisprediction     853273 ns       852790 ns          821 items_per_second=117.262M/s

 Performance counter stats for './01-mispredict':

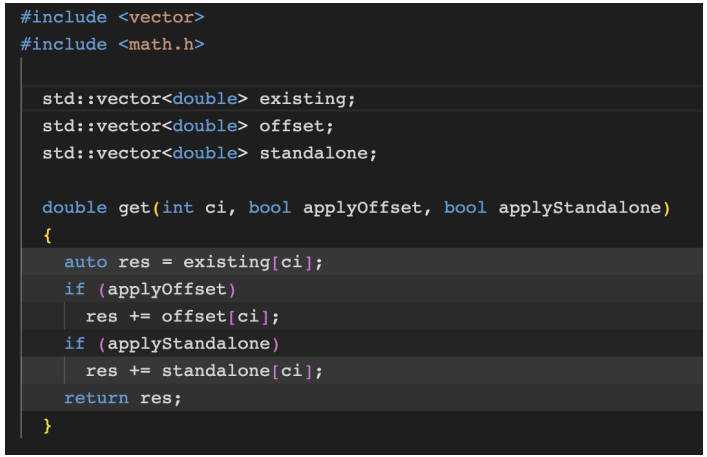
        829.819888      task-clock (msec)         #    0.975 CPUs utilized
                20      context-switches          #    0.024 K/sec
                 1      cpu-migrations            #    0.001 K/sec
              2035      page-faults               #    0.002 M/sec
        2312066437      cycles                    #    2.786 GHz
   <not supported>      stalled-cycles-frontend
   <not supported>      stalled-cycles-backend
        2235067958      instructions              #    0.97  insns per cycle
         353769199      branches                  #  426.320 M/sec
          46081671      branch-misses             #   13.03% of all branches
-----------------------------------------------------------------------------
Benchmark                   Time             CPU   Iterations UserCounters...
-----------------------------------------------------------------------------
BranchPrediction        506101 ns       502065 ns         1383 items_per_second=199.177M/s

 Performance counter stats for './01-predict':

        786.186525      task-clock (msec)         #    0.966 CPUs utilized
                78      context-switches          #    0.099 K/sec
                 1      cpu-migrations            #    0.001 K/sec
              2035      page-faults               #    0.003 M/sec
        2189915718      cycles                    #    2.785 GHz
   <not supported>      stalled-cycles-frontend
   <not supported>      stalled-cycles-backend
        3870538861      instructions              #    1.77  insns per cycle
         475422439      branches                  #  604.720 M/sec
             85181      branch-misses             #    0.02% of all branches
```

Bonus: Branchless Programming

Bonus: Branchless Programming



```cpp
#include <vector>
#include <math.h>

std::vector<double> existing;
std::vector<double> offset;
std::vector<double> standalone;

double get(int ci, bool applyOffset, bool applyStandalone)
{
  auto res = existing[ci];
  if (applyOffset)
    res += offset[ci];
  if (applyStandalone)
    res += standalone[ci];
  return res;
}
```

Bonus: Branchless Programming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Bonus: Branchless Programming

Qminers®

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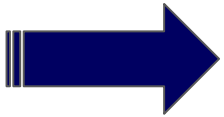

```
get(int, bool, bool):
        mov     rax, QWORD PTR existing[rip]
        movsx   rdi, edi
        movsd   xmm0, QWORD PTR [rax+rdi*8]
        test    sil, sil
        je      .L5
get(int, bool, bool):@6
        mov     rax, QWORD PTR offset[rip]
        addsd   xmm0, QWORD PTR [rax+rdi*8]
.L5:
        test    dl, dl
        je      .L4
.L5:@11
        mov     rax, QWORD PTR standalone[rip]
        addsd   xmm0, QWORD PTR [rax+rdi*8]
.L4:
        ret
```

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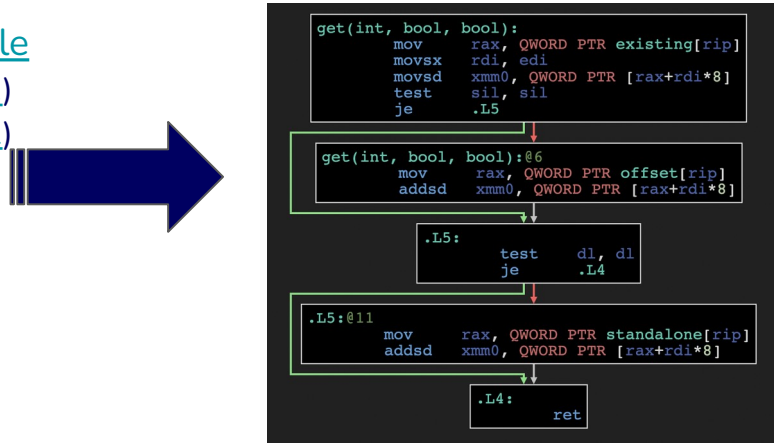
[Godbolt example](#)
([QuickBench #1](#))
([QuickBench #2](#))

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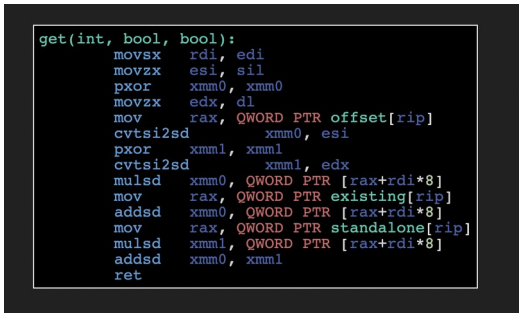
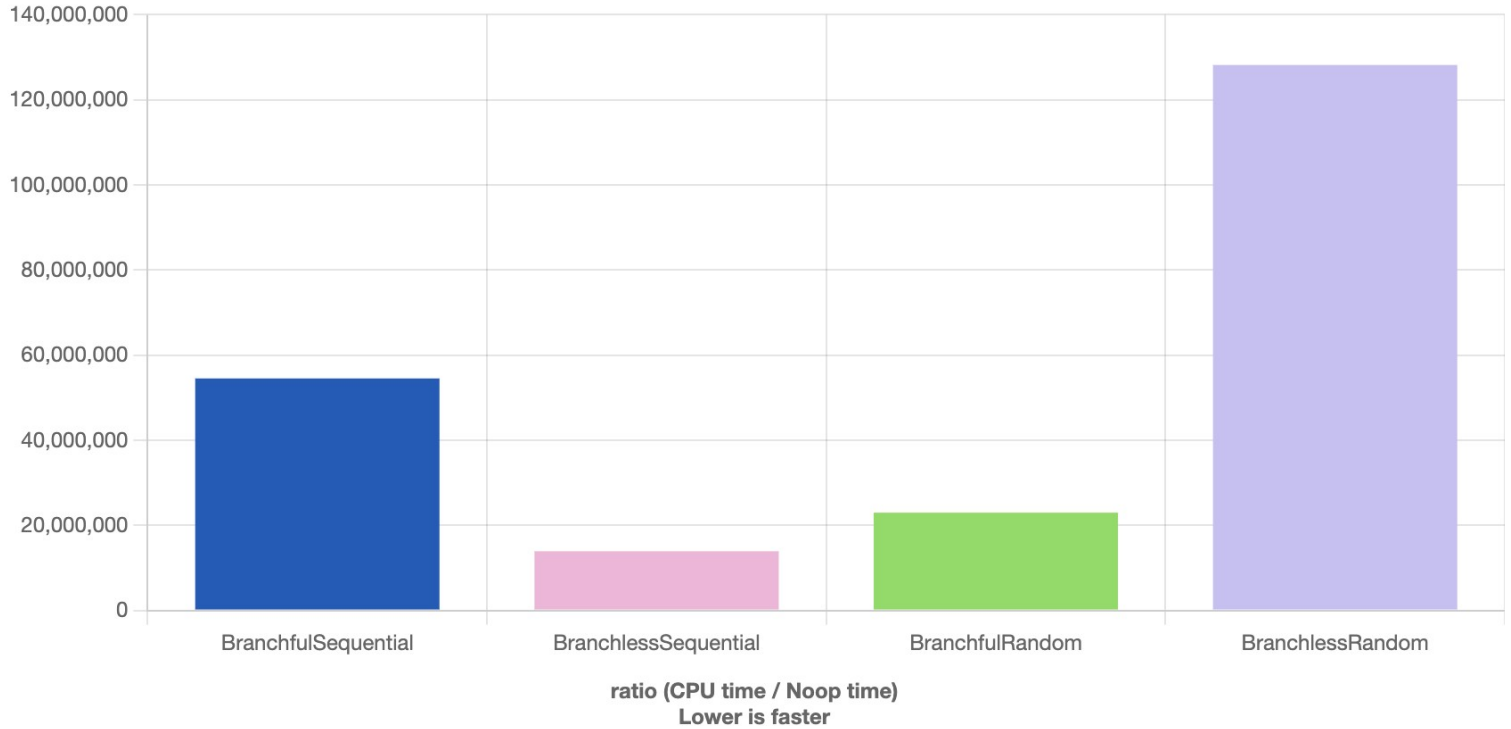


Bonus: Branchless Programming

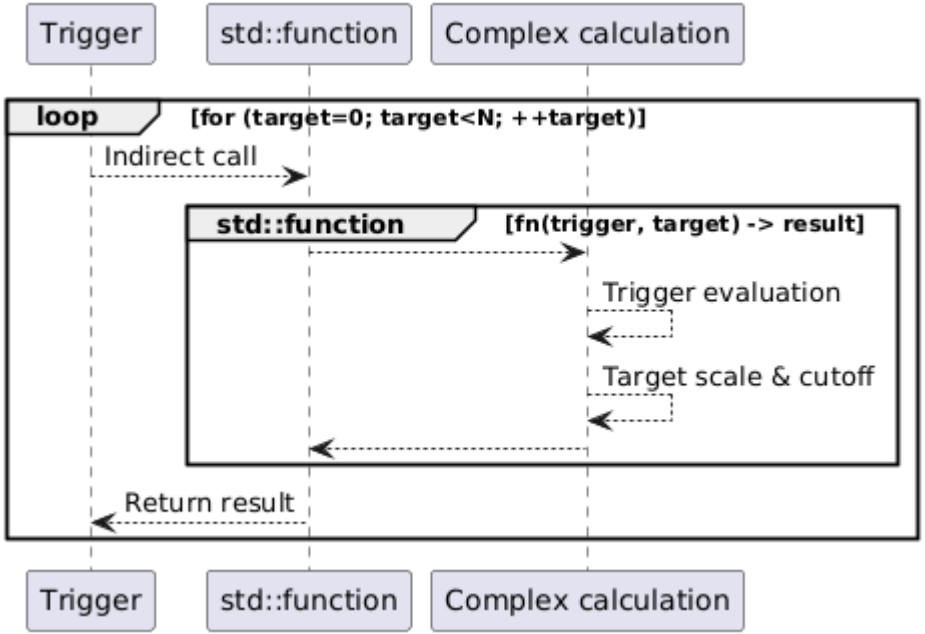


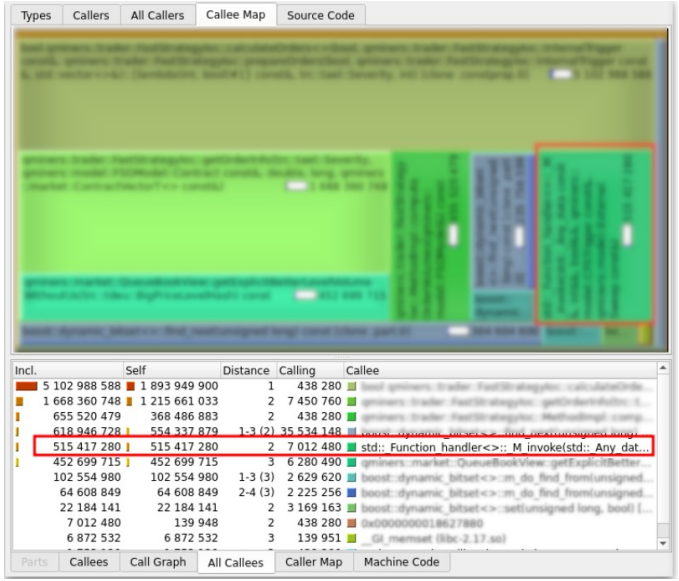
Bonus: Indirect Calls

Bonus: Indirect Calls

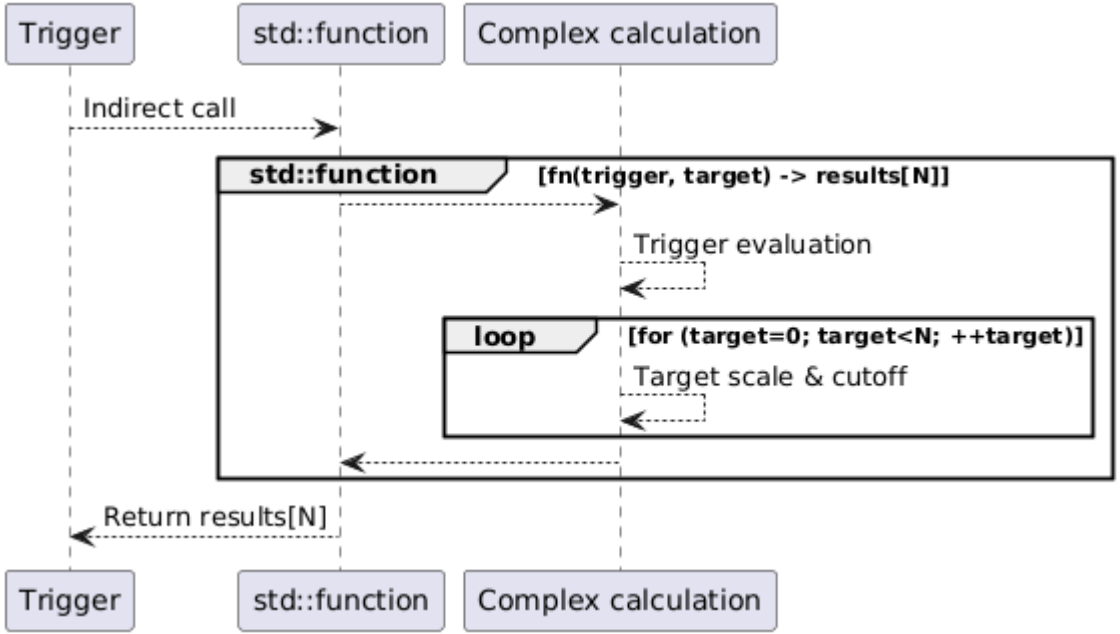
- Nepřímé volání
  - Poměrně drahé
    - Branch misprediction, icache miss, optimalizace
    - Snažíme se mu vyhnout (v kritickém kódu)
  - Jen když ho opravdu potřebujeme
    - “inheritance” (*interface*)
    - “type erasure” (*std::function*)
- Správná granularita
  - Kód je třeba dobře strukturovat
  - Měřit
  - Experimentovat

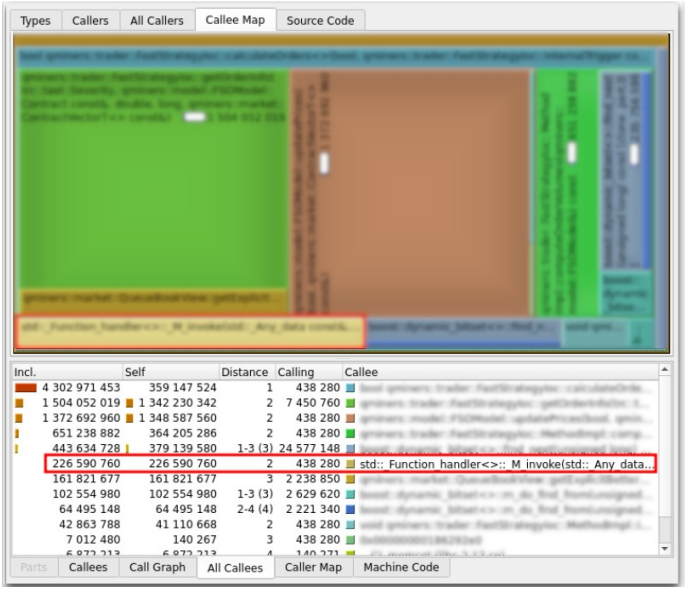
Bonus: Indirect Calls





Bonus: Indirect Calls

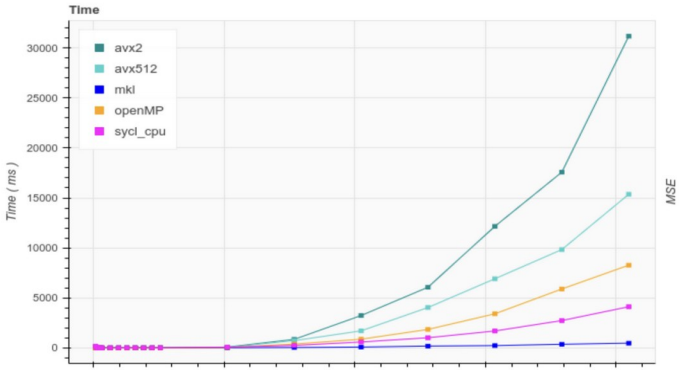




Bonus: Efficiency vs. Effectiveness

Bonus: Efficiency vs. Effectiveness

1) **Lineární algebra**
   a) Použití MKL (Math Kernel Library)
   b) Malé matice a vektory, rozklad na block-diagonal-matrix



Bonus: Efficiency vs. Effectiveness

Qminers

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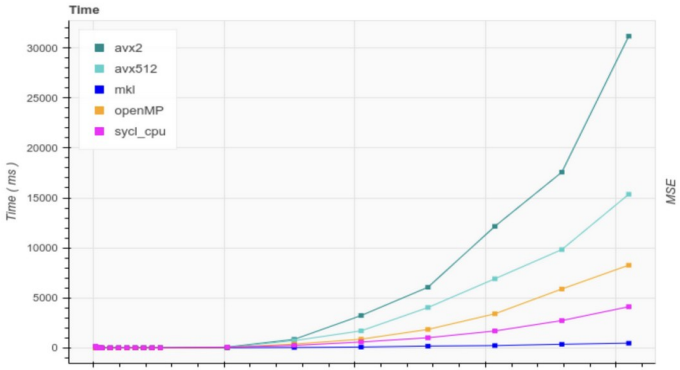

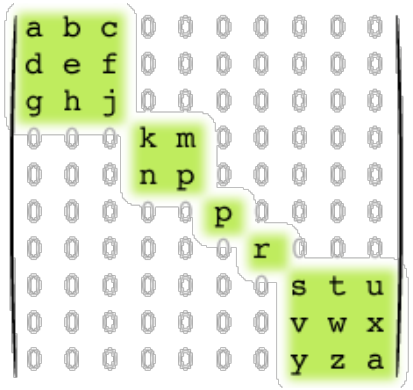

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Qminers®

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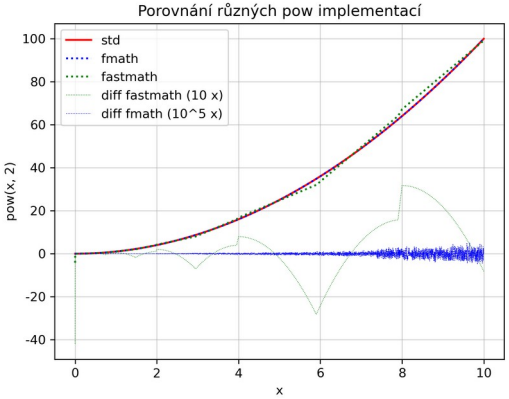
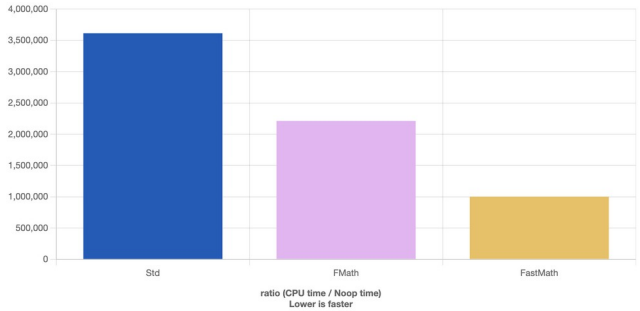
   a) Použití knihoven (std, fmath, fastmath, ...)
   b) Je nutné volat *pow(x, alpha)*, když *alpha == 1.05*?





Godbolt example

Bonus: Efficiency vs. Effectiveness

Qminers

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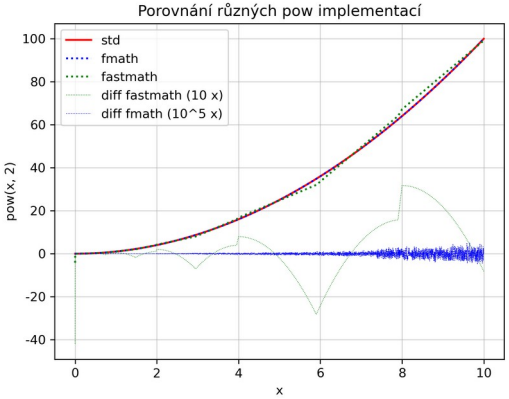

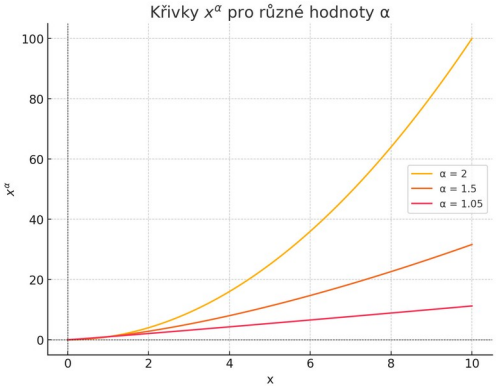

Godbolt example