Altimesh Hybridizer™

Embrace Micro-Architecture Changes

Abstract-Out Instruction Set Variety

Achieve State-Of-The-Art Performance

Finance and Regulation

- Financial institutions are very creative
  - Derivative products ecosystem grows constantly
  - Some players introduce new product types to leverage corner unregulated financial traits [e.g. Subprimes]
- Every big financial event yields new regulations
  - More stress scenarios [Too big to fail]
  - More complex financial quantitative models [Liquidity]
  - Higher number of simulations [unlikely systemic events]
- Quant analysts need to (re-)design quant libraries constantly
  - New models need to be developed, tested and integrated in existing system
  - Performance is getting critical: from thousands to millions of simulations – same power envelope ?
  - Code optimization gets low priority: following changes implied by regulators is already a heavy burden

Processor Ecosystem

- Processors have changed

year	*2000*	2014	2013	2012
processor	*Pentium 4*	Xeon E5-v3	Xeon PHI	Kepler
core frequency (GHz)	*3,8*	2,3	1,24	0,745
vector unit size (DP)	*1*	4	8	32
pipelines / core	*1*	2	1	2
contexts	*1*	2	4	4
core count	*1*	18	61	15
FMA	*1*	2	2	2
Peak scalar GFLOPS	*3,8*	165,6	151,28	22,35
Peak GFLOPS (DP)	*3,8*	662,4	1210,24	1430,4
SIMD/SIMT ratio	***1***	**4**	**8**	**64**
Bandwidth (R/W)	*4,26*	68	352	288
flop / memop	***7,14***	**77,93**	**27,51**	**39,73**
Bandwidth / core	*4,26*	3,78	5,77	19,20

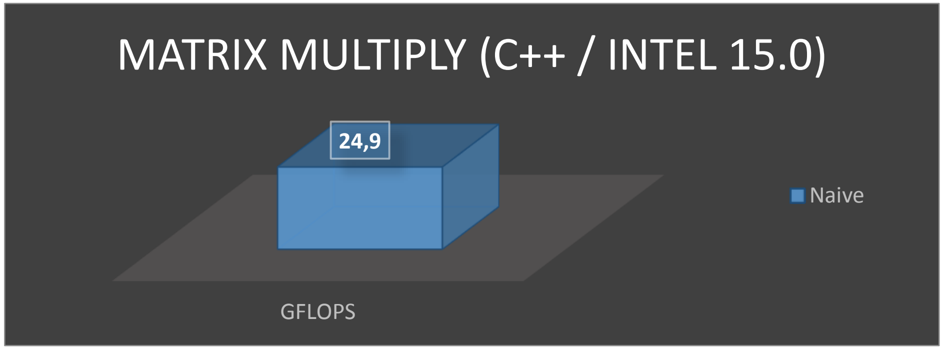
- Frequency drops, Core count / vector unit explodes
- Most problems get memory bound (flop / memop > 25)
- Multithreading is not the only issue (SIMD/SIMT ratio)

- Keeping-up with technology changes requires significant software development effort and training

Matrix Multiply

Naive Matrix Multiply

```
#pragma omp parallel for
for (int i = 0 ; i < rowsA ; ++i)
{
    for (int j = 0 ; j < colsB ; ++j)
    {
        double d = 0.0 ;
        for (int k = 0 ; k < colsA ; ++k)
        {
            d += A[i * colsA + k] * B[k * colsB + j] ;
        }
        C[i * colsB + j] = d ;
    }
} // */
```



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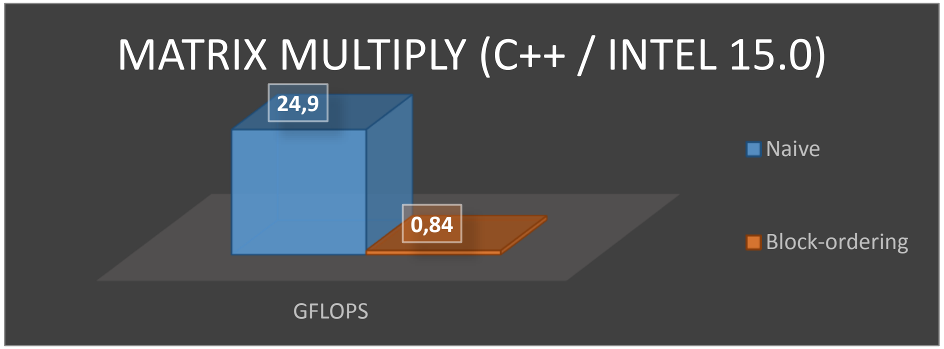
        }
        C[i * colsB + j] = d ;
    }
} // */
```

Block-accumulation (better cache behavior?)

```
#pragma omp parallel for default(none) firstprivate(rowsA, colsA, A, colsB, B, C)
for(int ibk = 0 ; ibk < rowsA / SIZE ; ++ibk)
{
    for (int jbk = 0 ; jbk < colsB / SIZE ; ++jbk)
    {
        for (int i = ibk * SIZE ; i < (ibk + 1) * SIZE ; ++i)
        {
            for (int j = jbk * SIZE ; j < (jbk + 1) * SIZE ; ++j)
            {
                double d = 0.0 ;
                for (int k = 0 ; k < colsA ; ++k)
                {
                    d += A[i * colsA + k] * B[k * colsB + j] ;
                }
                C[i * colsB + j] = d ;
            }
        }
    }
} // */
```



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{
    for (int jbk = 0 ; jbk < colsB / SIZE ; ++jbk)
    {
        for (int i = ibk * SIZE ; i < (ibk + 1) * SIZE ; ++i)
        {
            for (int j = jbk * SIZE ; j < (jbk + 1) * SIZE ; ++j)
            {
                double d = 0.0 ;
                for (int k = 0 ; k < colsA ; ++k)
                {
                    d += A[i * colsA + k] * B[k * colsB + j] ;
                }
                C[i * colsB + j] = d ;
            }
        }
    }
} // */
```
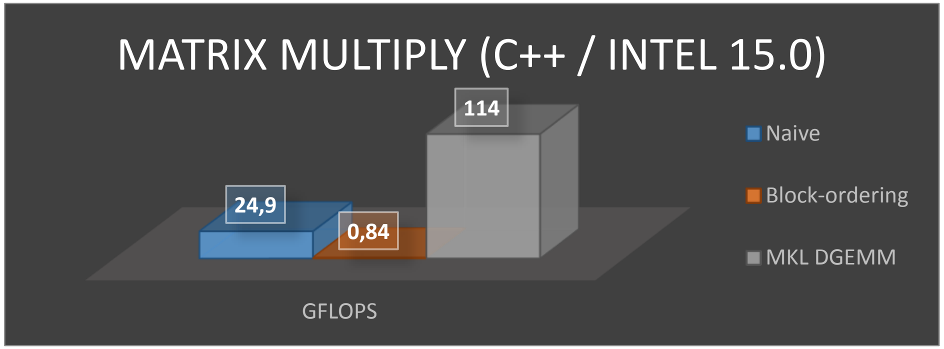



Matrix-Multiply sounds simple, however it involves advanced features:

- Vector-unit operations
- Non-temporal write
- Several layers of memory prefetching
- Many corner cases for unaligned sizes, transposes, etc.

Prefer Vendor-Tuned Libraries

Use Vendor-Tuned Libraries

- « What every programmer should know about memory », by *Ulrich Drepper*
  - It takes a lot to write (close to) optimal code
  - Understanding of core components of the system are necessary to get good performance (getting a compute-bound implementation of matrix multiply is hard)
- Micro-architecture evolve
  - AVX means 256 bits operands => new instruction set wrt SSE
  - AVX-2 has more instructions => need to redefine some code (see gather instruction)
  - AVX-512 is totally different, moreover flops/memops ratio evolves => need to rewrite
- Vendors provide optimized libraries (Intel MKL)
  - Prefer optimized libraries over hand-written versions
  - Sometimes better performance writing code to transition from custom code to optimized library
- Hybridizer integrates these libraries with Extensibility attributes
  - Available through wrapper methods (no overhead)
  - No overhead using these libraries
  - Same approach to integrate existing in-house developments

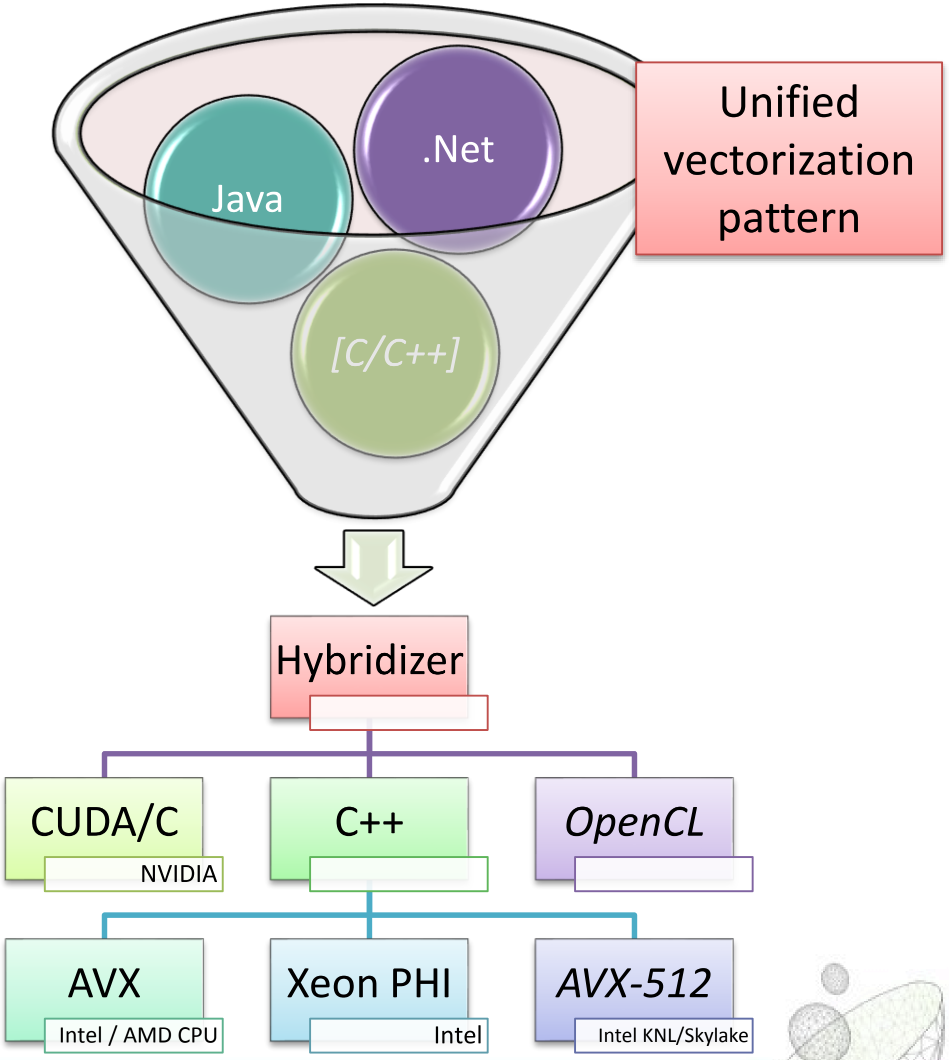
Key Changes to Embrace

- **Multithread** : core count explode, and frequency stalls or decrease => **not using multithread** will lead to **performance decrease** in the future
- **Vectorize** : vector unit size grows. SIMD/SIMT ratio indicates the relative loss when not *vectorizing* code. AVX-512 will double the fall for Intel x86 architecture.
- **Cache-aware** : flop/memop increase (> 25). Operations need to occur in cache. Large vector operations are memory bound and should be replaced by small vector operations

Hybridizer aims at addressing these challenges with a unified approach

Hybridizer Solution

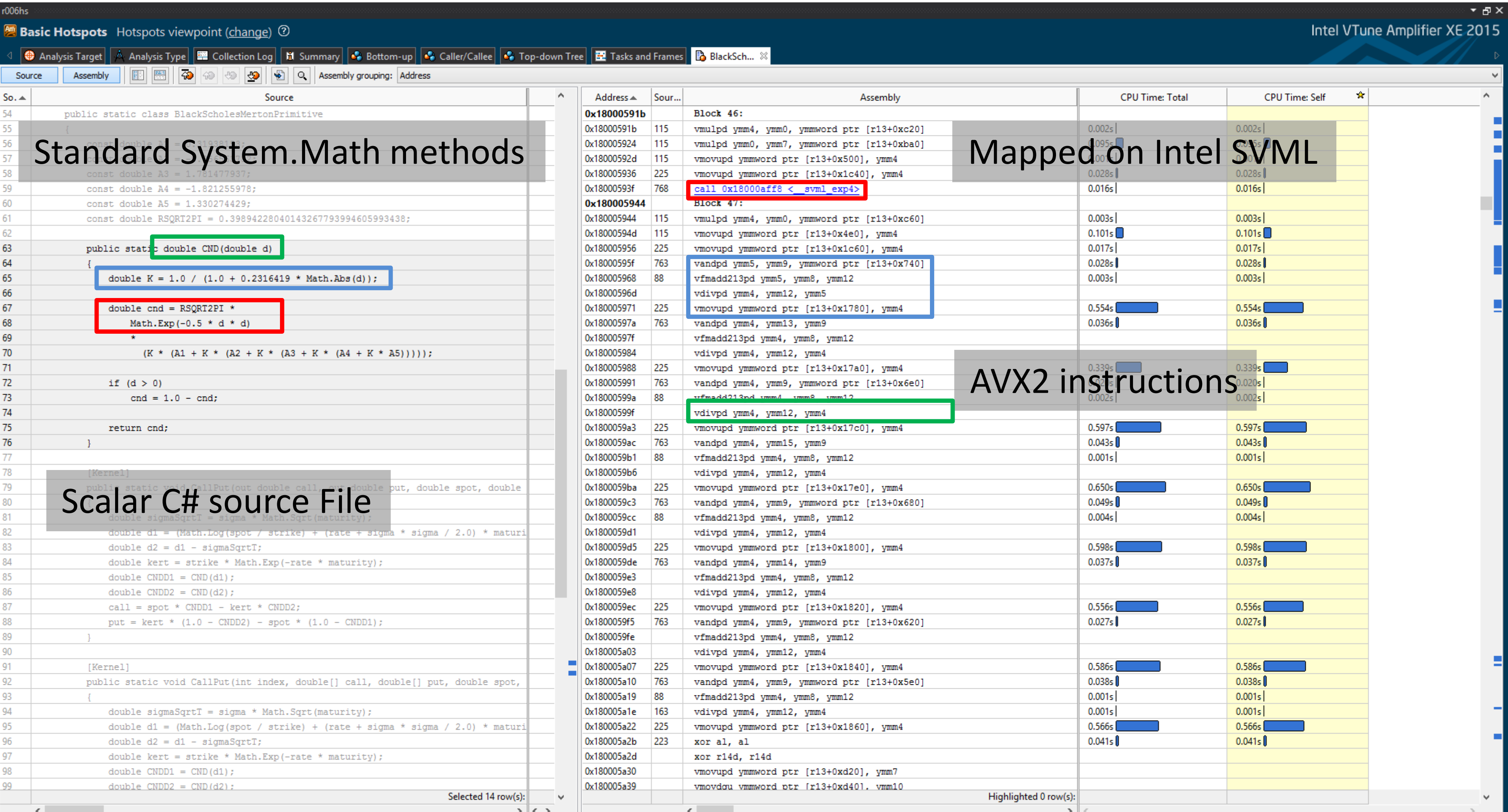
- Input
  - .Net
  - Java
  - *C/C++* *(ongoing developments)*
- Environments:
  - Windows / Linux
- Generate source code
  - CUDA/C for NVIDIA GPU
  - C++ for native platforms
  - Open CL



Hybridizer Benefits

- **Single version of source code**
  - Express parallelism with a paradigm of choice (ParallelFor / iterators / custom indexing type)
  - Generates several flavors of source code
- **Execution on a variety of platforms**
  - Plain C, CUDA
  - Vector-units: AVX, AVX2, AVX-512
  - External libraries integration (e.g. MKL) and extensibility (hand-tuned micro-architecture specific codes)
- **Debugging / Profiling of output**
  - Code location is preserved on target platform
  - Integration in existing debugging / profiling tools
  - Generated source-code is readable for auditing

Integration with Intel Vtune Amplifier



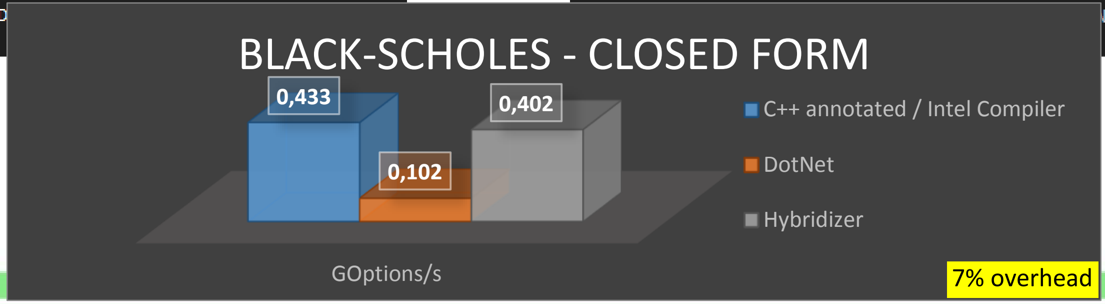
Benchmark-Level Performances

C#

```csharp
const double A1 = 0.31938153;
const double A2 = -0.356563782;
const double A3 = 1.781477937;
const double A4 = -1.821255978;
const double A5 = 1.330274429;
const double RSQRT2PI = 0.39894228040143267793994605993438;

public static double CND(double d)
{
    double K = 1.0 / (1.0 + 0.2316419 * Math.Abs(d));

    double cnd = RSQRT2PI *
        Math.Exp(-0.5 * d * d)
        *
          (K * (A1 + K * (A2 + K * (A3 + K * (A4 + K * A5)))));

    if (d > 0)
        cnd = 1.0 - cnd;

    return cnd;
}

[Kernel]
public static void CallPut(out double call, out double put,
    double spot, double strike,
    double rate, double sigma, double maturity)
{
    double sigmaSqrtT = sigma * Math.Sqrt(maturity);
    double d1 = (Math.Log(spot / strike) + (rate +
        sigma * sigma / 2.0) * maturity) / sigmaSqrtT;
    double d2 = d1 - sigmaSqrtT;
    double kert = strike * Math.Exp(-rate * maturity);
    double CNDD1 = CND(d1);
    double CNDD2 = CND(d2);
    call = spot * CNDD1 - kert * CNDD2;
    put = kert * (1.0 - CNDD
}
```

C++

```cpp
static double cnd(double d)
{
    const double       A1 = 0.31938153;
    const double       A2 = -0.356563782;
    const double       A3 = 1.781477937;
    const double       A4 = -1.821255978;
    const double       A5 = 1.330274429;
    const double RSQRT2PI = 0.39894228040143267793994605993438;

    double
    K = 1.0 / (1.0 + 0.2316419 * fabs(d));

    double
    cnd = RSQRT2PI * exp(- 0.5 * d * d) *
          (K * (A1 + K * (A2 + K * (A3 + K * (A4 + K * A5)))));

    if (d > 0)
        cnd = 1.0 - cnd;

    return cnd;
}

static void bsm(double& call, double& put, double S0,
                double K, double r, double sigma, double T)
{
    double sigmaSqrtT = sigma * ::sqrt (T) ;
    double d1 = (::log(S0/K) + (r + sigma*sigma/2.0) * T) / sigmaSqrtT ;
    double d2 = d1 - sigmaSqrtT ;
    double kert = K * ::exp (-r * T) ;
    double CNDD1 = cnd(d1);
    double CNDD2 = cnd(d2);
    call = S0 * CNDD1 - kert * CNDD2;
NDD1) ;
```



Extended features

Virtual Functions

- Interfaces / abstract classes and inheritance is supported
- Underlying implementation is a function-table

Object oriented programming productivity maintained …

Generics

- Generics get mapped onto templates
- C++ template concepts are expressed by DotNet/Java generics constraints
- Restored performance

… And overhead can be removed

Financial Model Spot Diffusion

Dot net source code
Generic parameters for flexibility

C#

```
[Kernel]
public void Diffusion(
    int simFrom, int simTo,
    int timeFrom, int timeTo,
    Volatility volatility,
    Rate rate,
    LogSpot logSpot,
    Brownian brownian,
    Schedule schedule)
{
    for (alignedindex simId = VectorUnit.ID + simFrom;
        simId < simTo; simId += VectorUnit.Count)
    {
        double lnSk = logSpot[simId, timeFrom];
        for (int t = timeFrom; t < timeTo; ++t)
        {
            double sigma = volatility[lnSk, simId, t];
            double sqrtdt = schedule.getSqrtDT(t);
            double dt = schedule.getDT(t);
            lnSk += (sigma * brownian[simId, t] * sqrtdt) +
                (rate[simId, t] - 0.5 * sigma * sigma) * dt;
            logSpot[simId, t + 1] = lnSk;
        }
    }
}
```

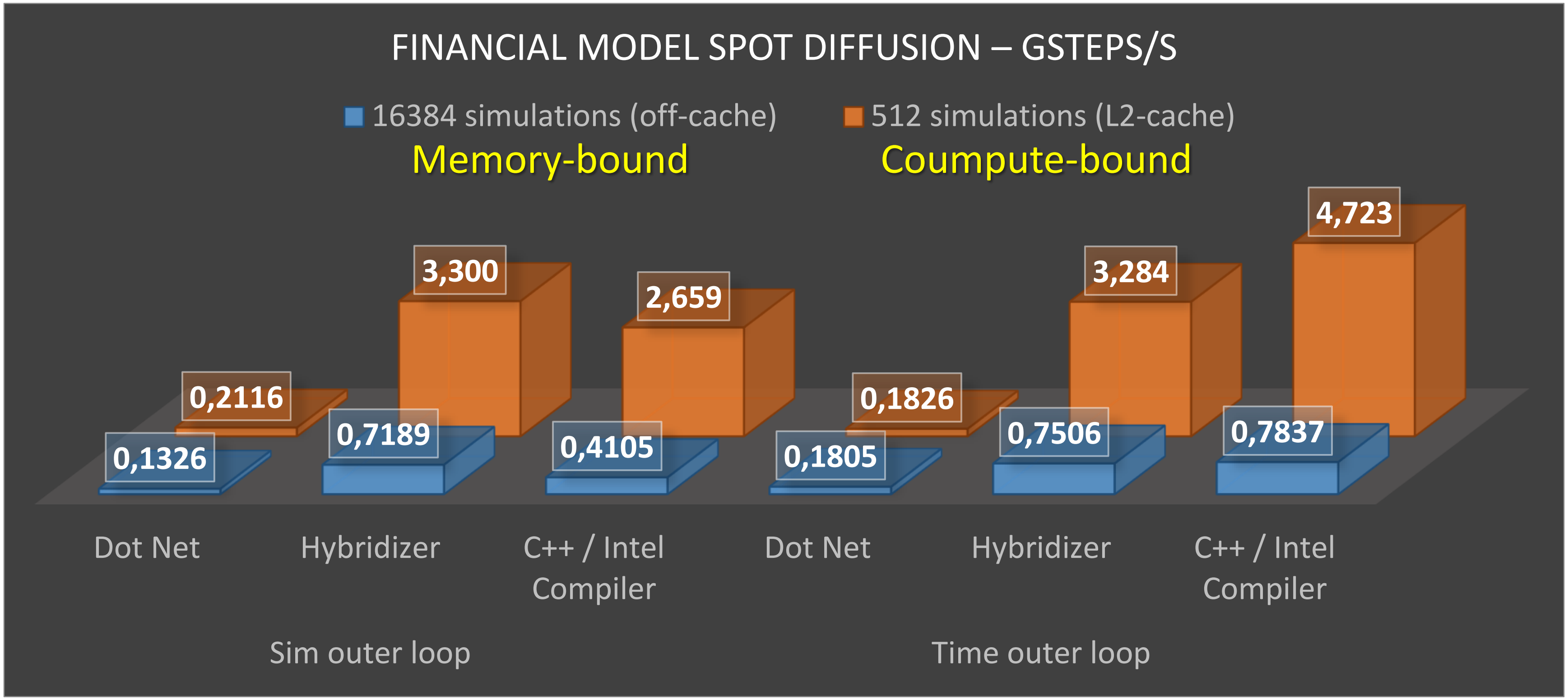
C++ source code with annotations
(two outer loop configurations)

C++

```
void diffuse (int simCount, int datesCount,
              const double* __restrict dates,
              const double* __restrict DT,
              const double* __restrict sqrtDT,
              const double* __restrict brownian,
              double* __restrict logSpot,
              double sigma, double rate)
{
    #pragma omp parallel for
    #pragma simd
    #pragma ivdep
    for (int simId = 0 ; simId < simCount ; ++simId)
    {
        double lnS = logSpot [simId] ;
        for (int time = 0 ; time < datesCount ; ++time)
        {
            lnS += (sigma * brownian[time * simCount + simId] * sqrtDT[time]) +
                (rate - 0.5 * sigma * sigma) * DT[time];
            logSpot[(time+1) * simCount + simId] = lnS ;
        }
    }
}
```

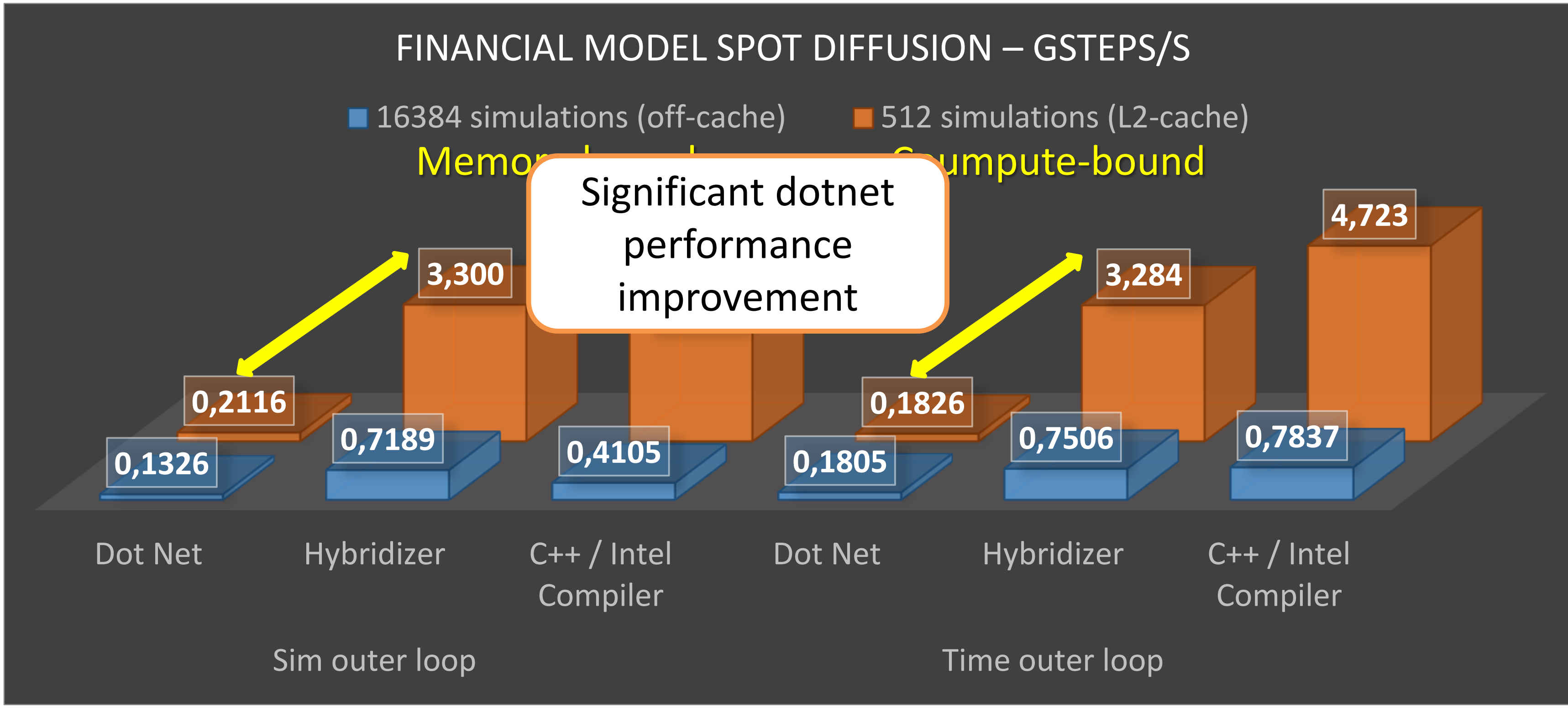
```
#pragma omp parallel for
for (int th = 0 ; th < 8 ; ++th)
{
    int simFrom = th * simCount / 8 ;
    int simTo = (th+1) * simCount / 8 ;
    for (int time = 0 ; time < datesCount ; ++time)
    {
        double* lnS = logSpot + (simCount * time) ;
        const double* brow = brownian + (time * simCount) ;
        #pragma ivdep
        #pragma simd
        for (int simId = simFrom ; simId < simTo ; ++simId)
        {
            lnS[simId + simCount] = lnS [simId] + (sigma * brow[simId] * sqrtDT[time]) + (rate - 0.5 * sigma * sigma) * DT[time];
        }
    }
}
```

Black-Scholes-Merton Diffusion



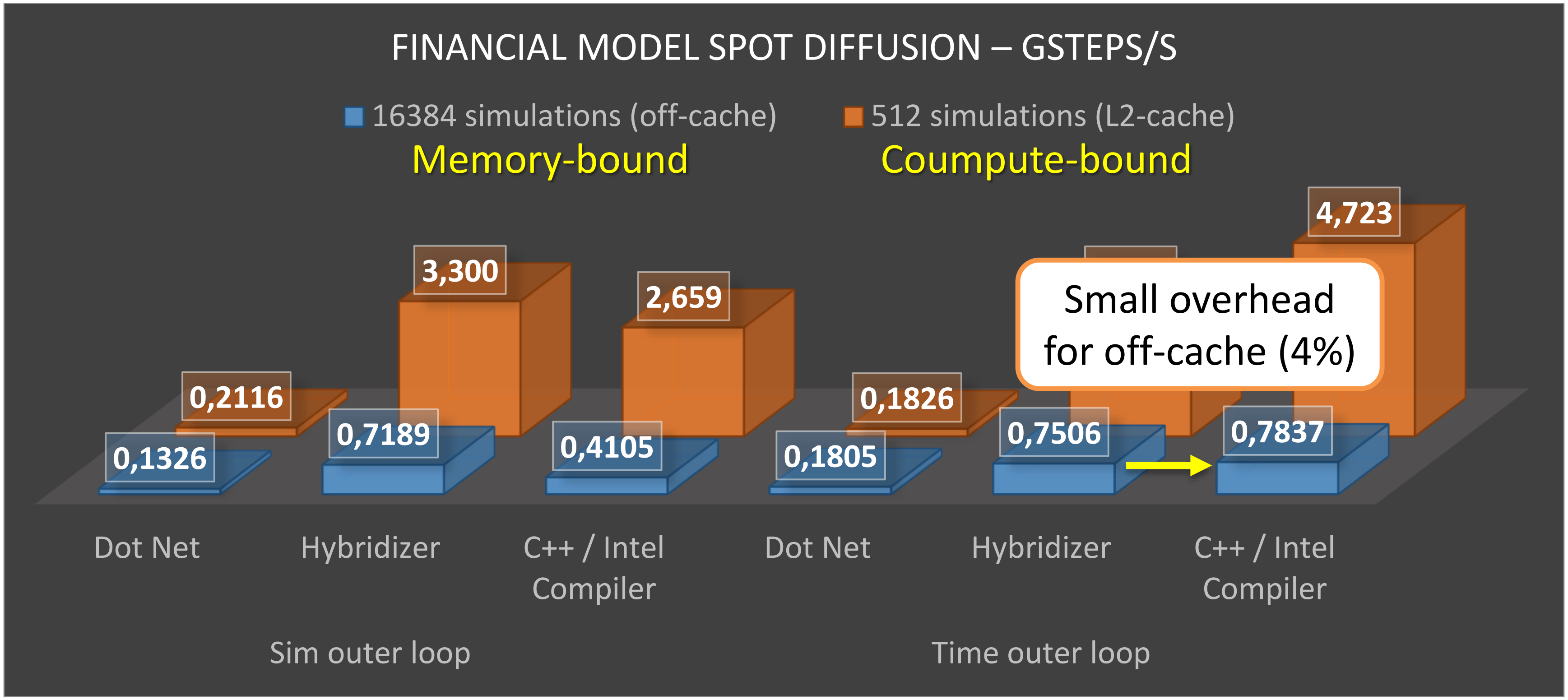
- **Comparing object-oriented code, with generics, processed by Hybridizer**
- **with hand-written optimized C++ code compiled with Intel Composer 2015**

Black-Scholes-Merton Diffusion



- **Hybridizer greatly improves dotnet performance: 5x to 18x**
- **Object oriented programming preserved: single version of source code, reduces operational risk / testing costs.**

Black-Scholes-Merton Diffusion



- **Hybridizer greatly improves dotnet performance: 5x to 18x**
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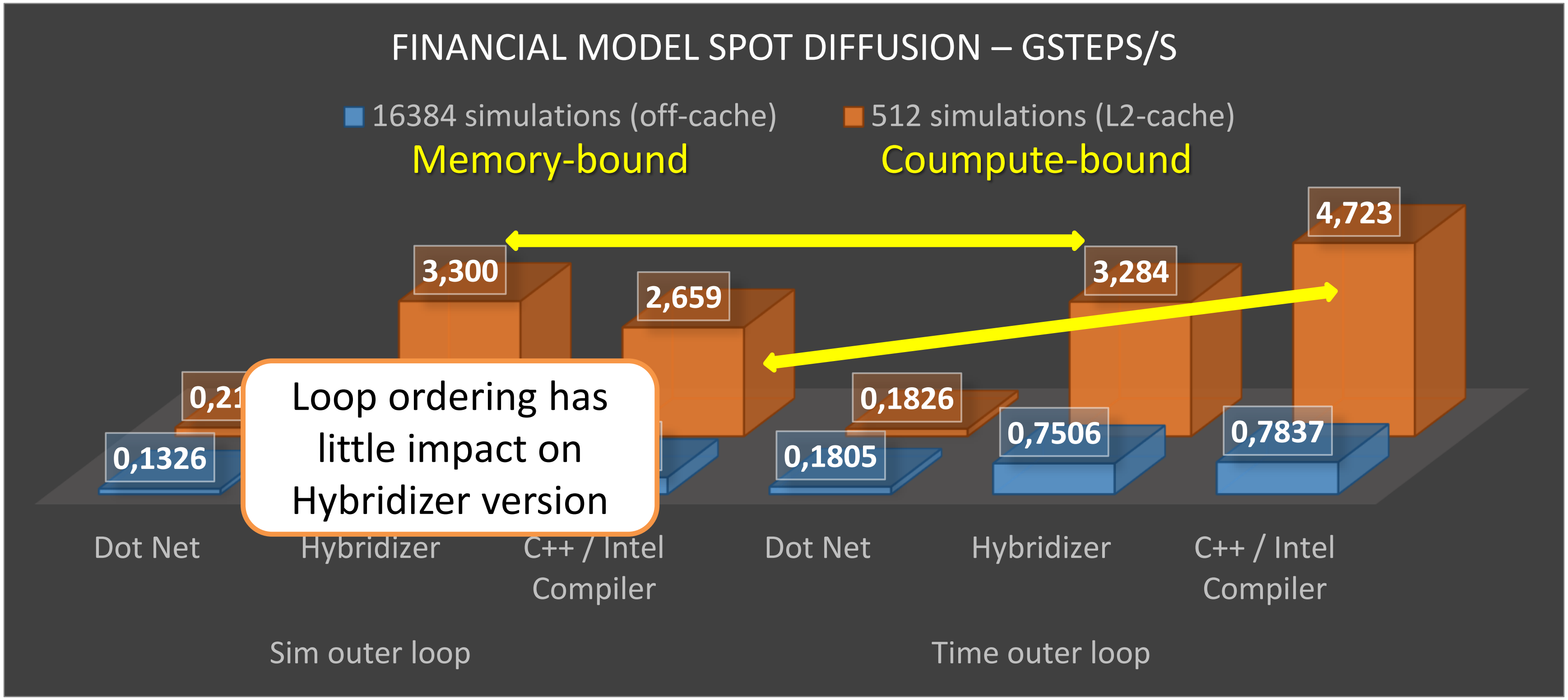
- **Hybridizer provides benchmark-level performances (96% of best performing off-cache)**

Black-Scholes-Merton Diffusion



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- **Object oriented programming preserved: single version of source code, reduces operational risk / testing costs.**
- **Hybridizer provides benchmark-level performances (96% of best performing off-cache)**
- **Loop ordering has little impact for Hybridizer version (~4%) yet large impact for hand-written implementation (>45%)**

NOTE: cache-locality and outer-loop selection has a **10x** impact on performance. Writing optimized C++ code requires significant effort and knowledge.

Conclusions

- Shortened development cycles
  - Single version of source code – with « managed » languages
  - Integrates with Debuggers and Profilers
- State-of-the art performances
  - Software development flexibility without performance costs
  - Close to Benchmark (>90%) for compute and memory bound problems
- Embrace micro-architecture changes
  - Hybridizer is AVX-512 ready – simply recompile ?

http://www.altimesh.com