Performance Portable Tracking of Evolving Surfaces

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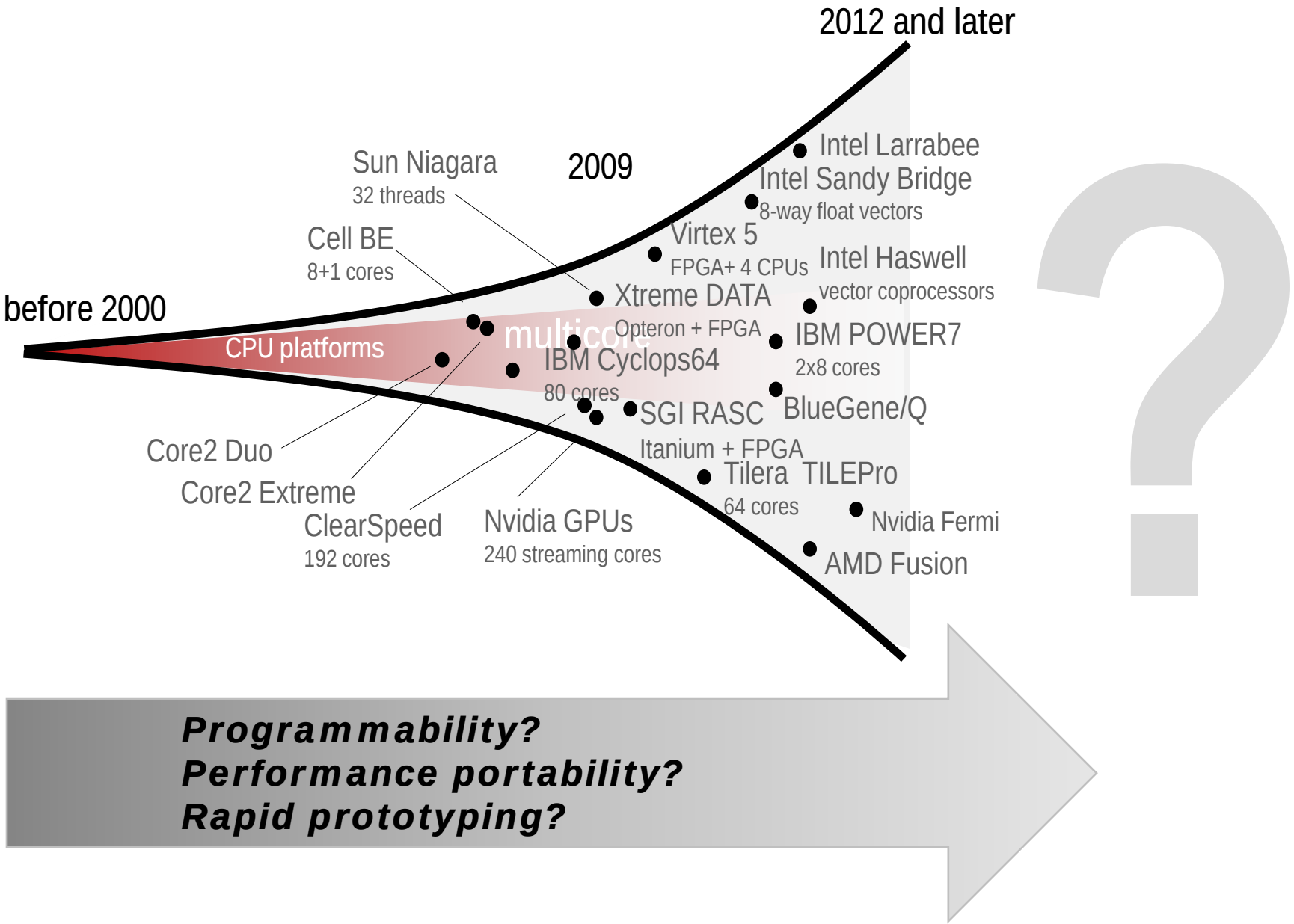
The Future is Parallel and Heterogeneous



Software's Slow Pace of Change

Popular performance programming languages

- **1953:** Fortran
- **1973:** C
- **1985:** C++
- **1997:** OpenMP
- **2007:** CUDA

Popular performance libraries

- **1979:** BLAS
- **1992:** LAPACK
- **1994:** MPI
- **1995:** ScaLAPACK
- **1995:** PETSc
- **1997:** FFTW

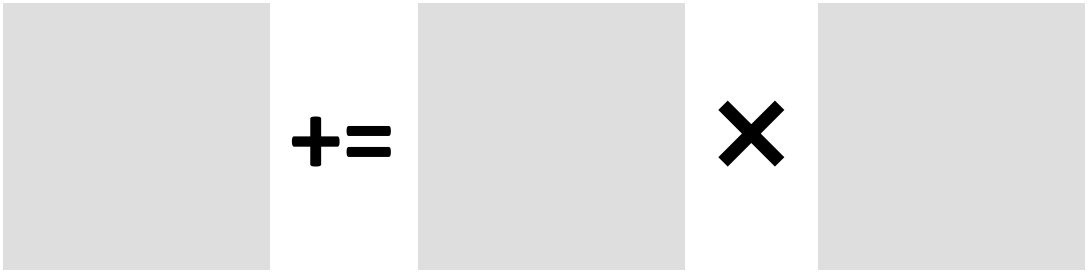
Popular productivity/scripting languages

- **1987:** Perl
- **1989:** Python
- **1993:** Ruby
- **1995:** Java
- **2000:** C#

Compilers: The Fundamental Problem

Matrix-matrix multiplication

```
for i=1:N
  for j=1:N
    for k=1:N
      C[i,j] += A[i,k]*B[k,j]
```



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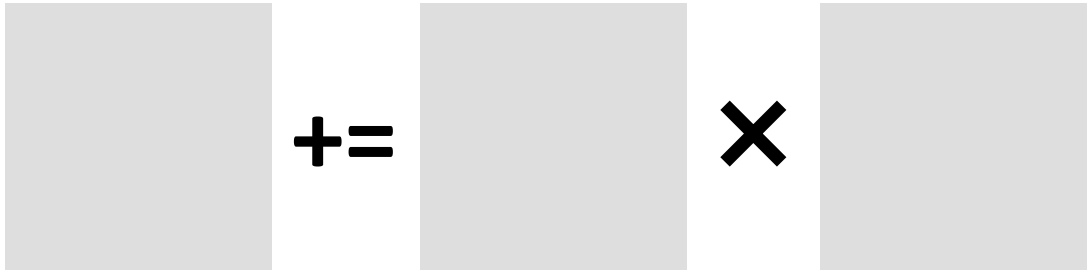
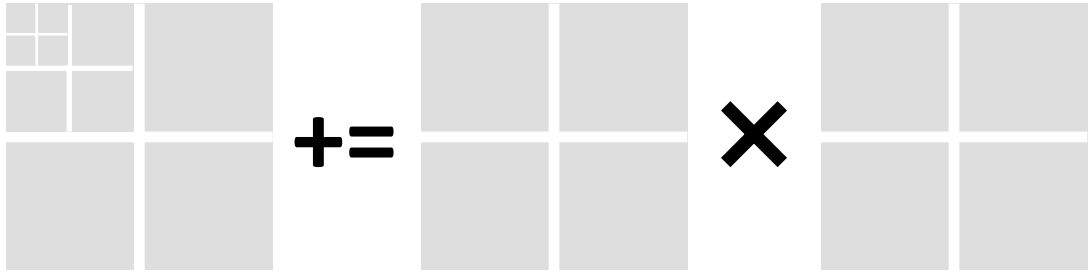


Tiled+unrolled+parallelized+SIMDized+prefetching matrix-matrix multiplication

```
#pragma omp parallel for
for i=1:NB:N
  for j=1:NB:N
    for k=1:NB:N
      for i0=i:NU:i+NB
        #pragma prefetch B
        for j0=j:NU:j+NB
          for k0=k:NU:k+NB
            #pragma unroll
            for k00=k0:1:k0+NU
              for j00=j0:1:j0+NU
                #pragma vector always
                for i00=i0:1:i0+NU
                  C[i00,j00] += A[i00,k00]*B[k00,j00];
```



Problem: which transformation order? What parameter values?

Autotuning and Program Synthesis

Synthesis from Domain Math

- **Spiral**
  Signal and image processing, SDR
- **Tensor Contraction Engine**
  Quantum Chemistry Code Synthesizer
- **FLAME**
  Numerical linear algebra (LAPACK)

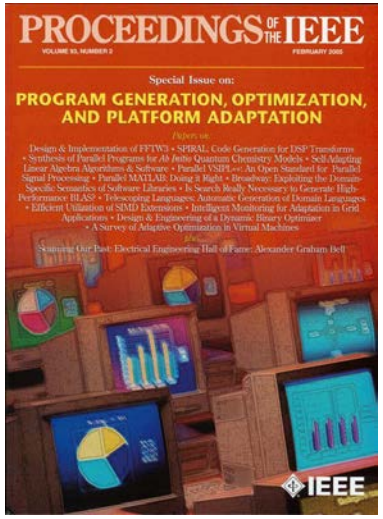
Compiler-Based Autotuning

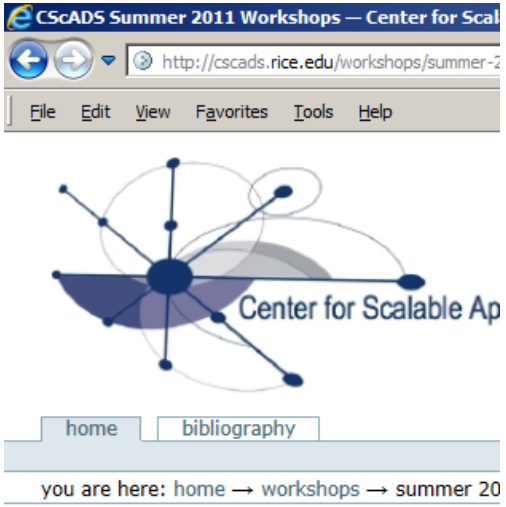
- **Polyhedral framework**
  IBM XL, Pluto, CHiLL
- **Transformation prescription**
  CHiLL, POET
- **Profile guided optimization**
  Intel C, IBM XL

Autotuning Numerical Libraries

- **ATLAS**
  BLAS generator
- **FFTW**
  kernel generator
- **Vendor math libraries**
  Code generation scripts

Autotuning Primer

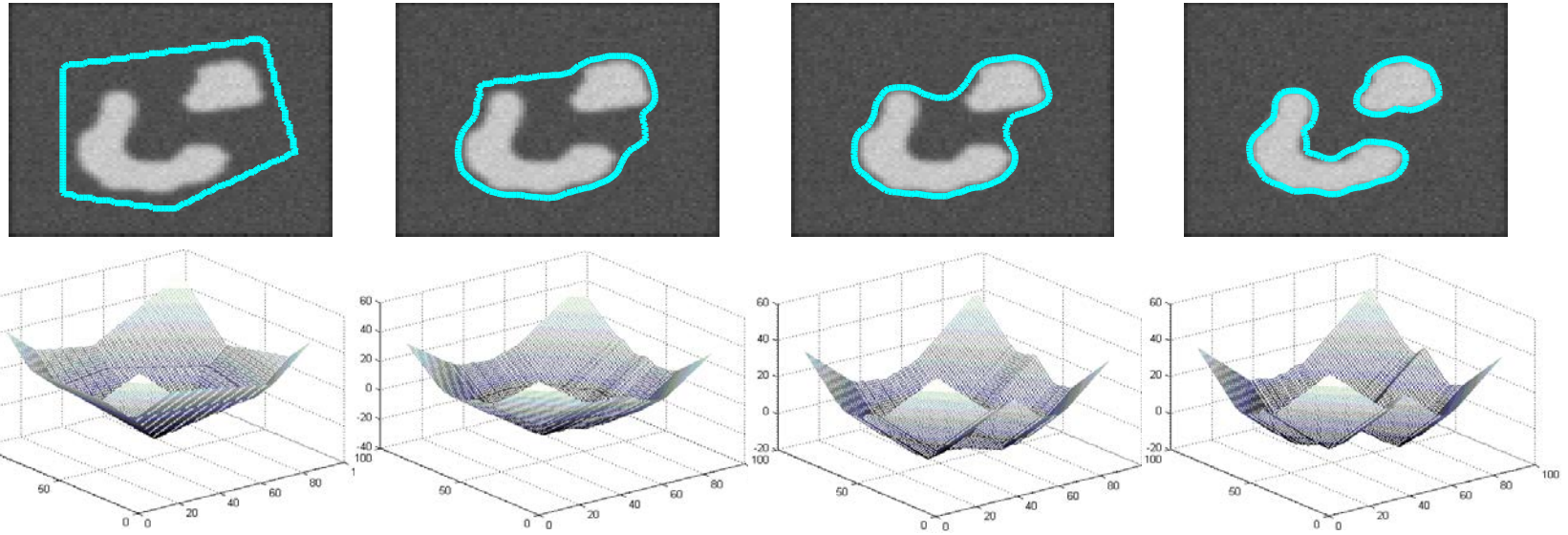




Level-Set Image Segmentation

Level Set Algorithm

- PDE-based image segmentation method
- Image produces force field on moving contour
- Embeds contour into n+1 dimensional level-set function



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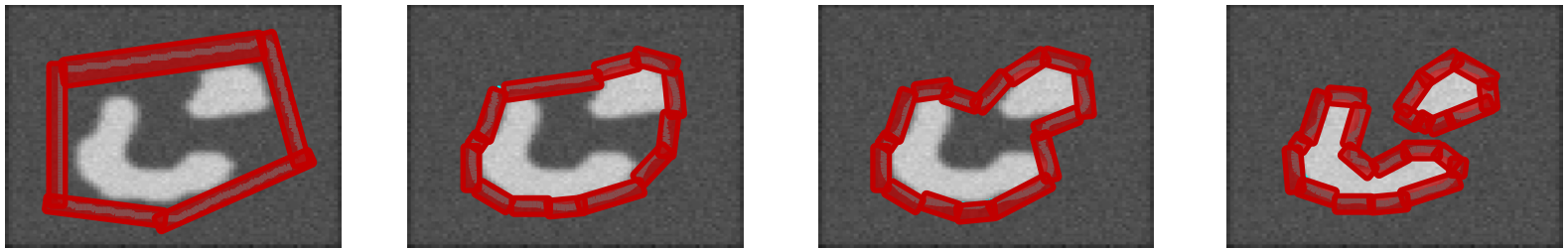
Narrow Band Level Set Algorithm

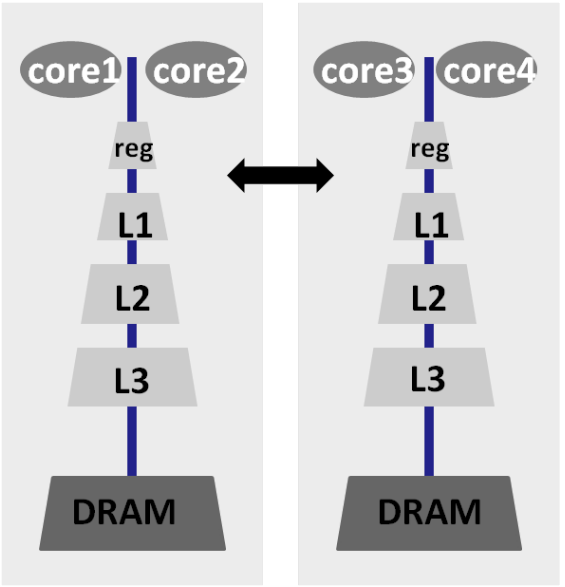
- Compute only in neighborhood of boundary
- Makes algorithm computationally tractable but complicated

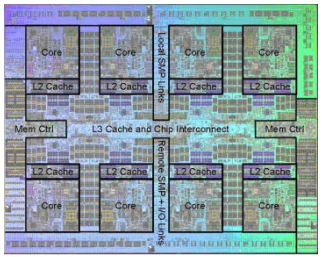


Target: Cache-Based Multicores

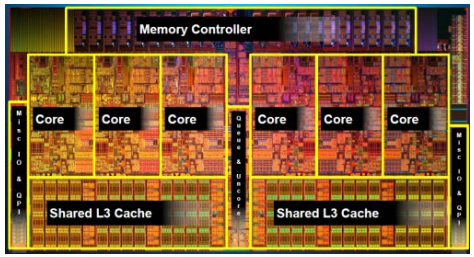
COTS Multicore

- Shared memory (SMP or NUMA)
- Cache-based memory (L1, L2, L3)
- SIMD vector instructions (SSE, AltiVec,…)

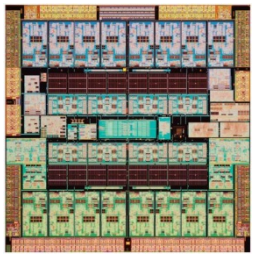




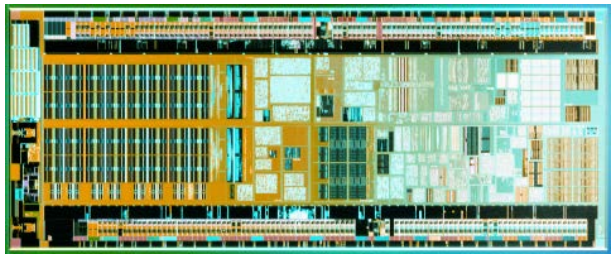
IBM POWER7
8 cores, 4-way SMT



Intel Core i7
8 cores, 2-way SMT



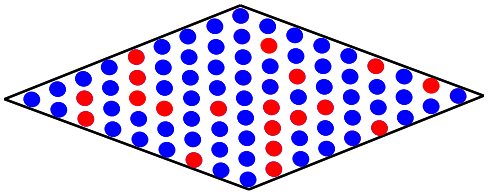
UltarSPARC T3
16 cores, 8-way SMT



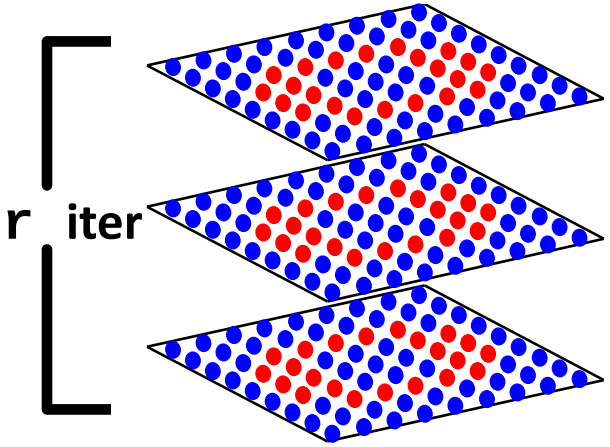
Intel Atom
1 cores, 2-way SMT

Why A Challenging Problem?

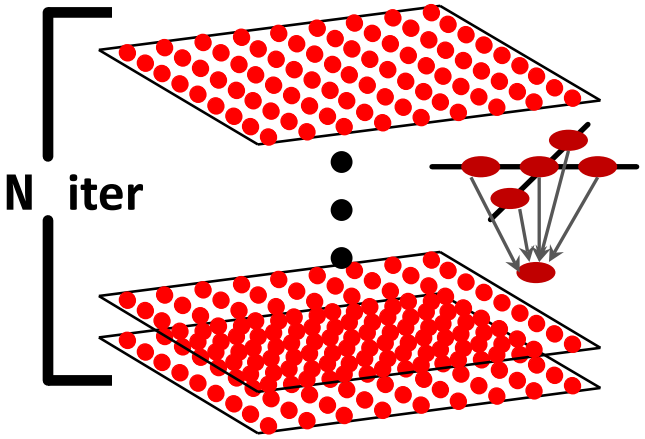
SparseMV



Narrow Band Level Set



Stencil



Memory bound

compute bound

O(1)

O(N)

sparse & irregular data structure	sparse data with dense substructure	dense & regular data structure

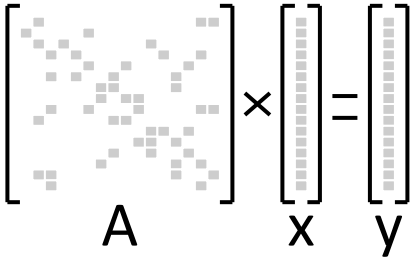
Approach

- **Understand algorithmic trade-offs**
  - Cheaper iterations vs. fewer iterations
  - Computation load vs. algorithm regularity
- **Understand the target hardware**
  - What are the costs and trade-offs?
  - What are good implementation choices and tricks?
- **Develop optimized parameterized implementation**
  - Parameters should expose machine/algorithm interaction
  - Parameterization may require macros or program generation
- **Autotune the algorithm and implementation parameters**
  - Parameter choice is unclear because of algorithm/architecture interaction
  - Autotuning is the last step in aggressive performance tuning

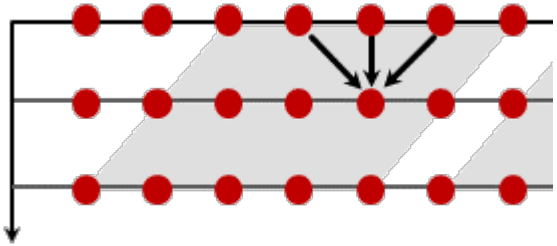
100x gain: *Optimized parameterized program: 50x, autotuning: 2x*

How to Get Level Set Up To Speed?

Sparse Linear Algebra



Time Skewing

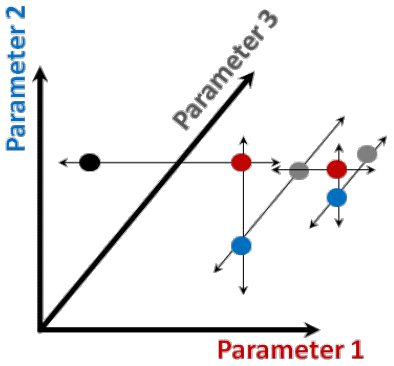


Code generation

```
for (int j=lj; j<=hj; j++)
  for (int i=li; i<=hi; i++)
    BI[j][i]=1;
```

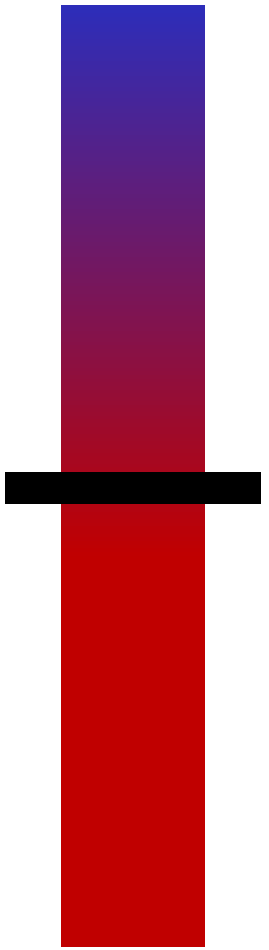
```
switch (case) {
  case (…):
    BI[j-1][i-1]=1;
    …
    BI[j+1][i+1]=1;
    break;
  case (…):
    …
}
```

Auto-tuning

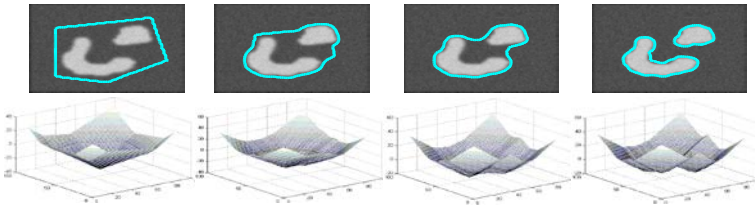


How Far Did We Go?

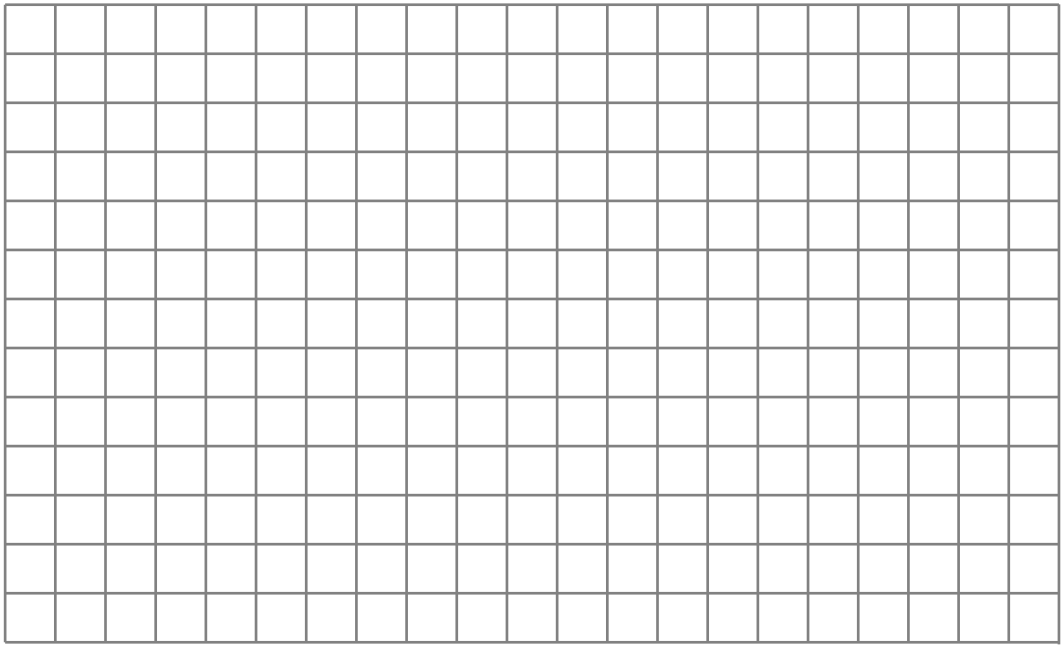
- **Level 0: simple C program**
  implements the algorithm cleanly
- **Level 1: C macros plus autotuning search script**
  use C preprocessor for meta-programming
- **Level 2: autotuning + scripting for code specialization**
  text-based program generation, specialization
- **Level 3: add compiler technology, synthesize parts**
  internal code representation, standard compiler passes
- **Level 4: synthesize the whole program from scratch**
  high level representation, domain-specific synthesis



Narrow Band Level Set in a Nutshell



$$\phi^{t+1} = \Gamma(\phi^t(x \pm \Delta_x, y \pm \Delta_y))$$



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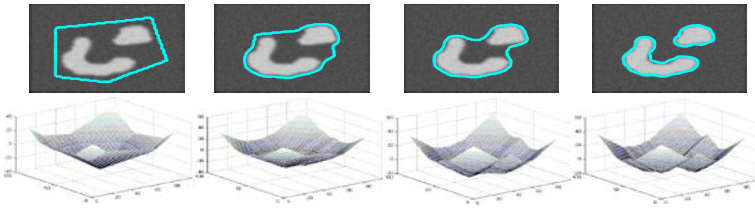

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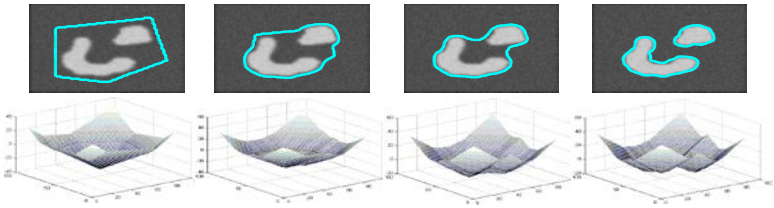

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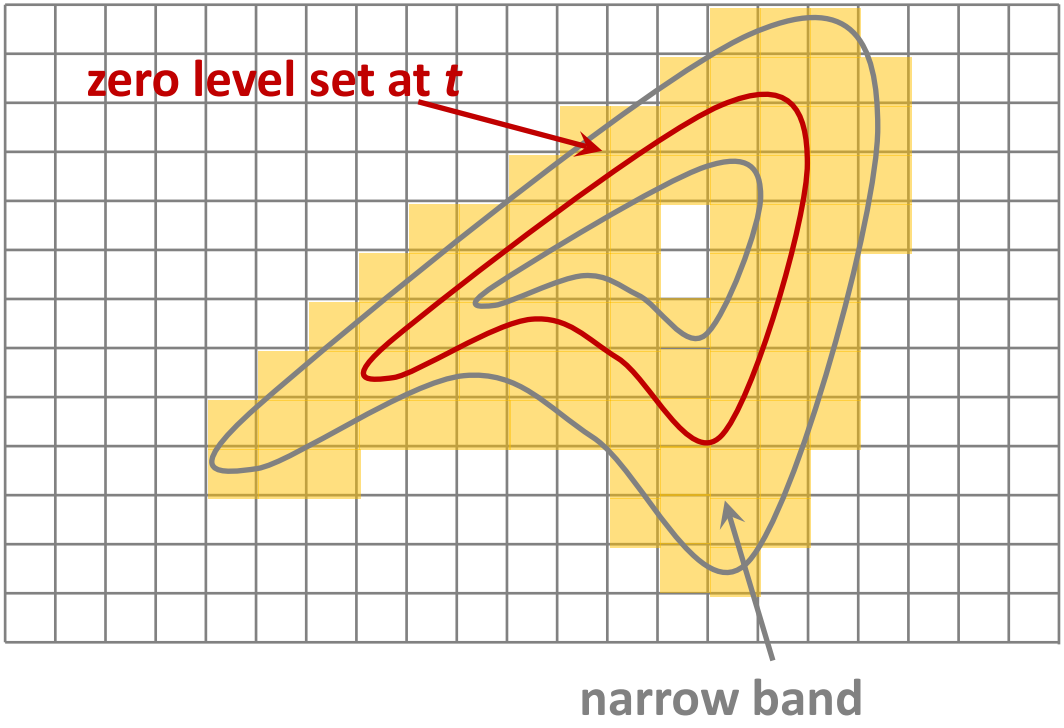

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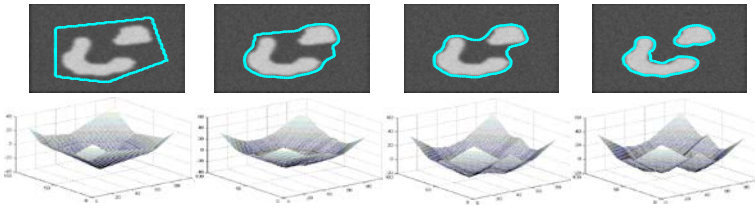

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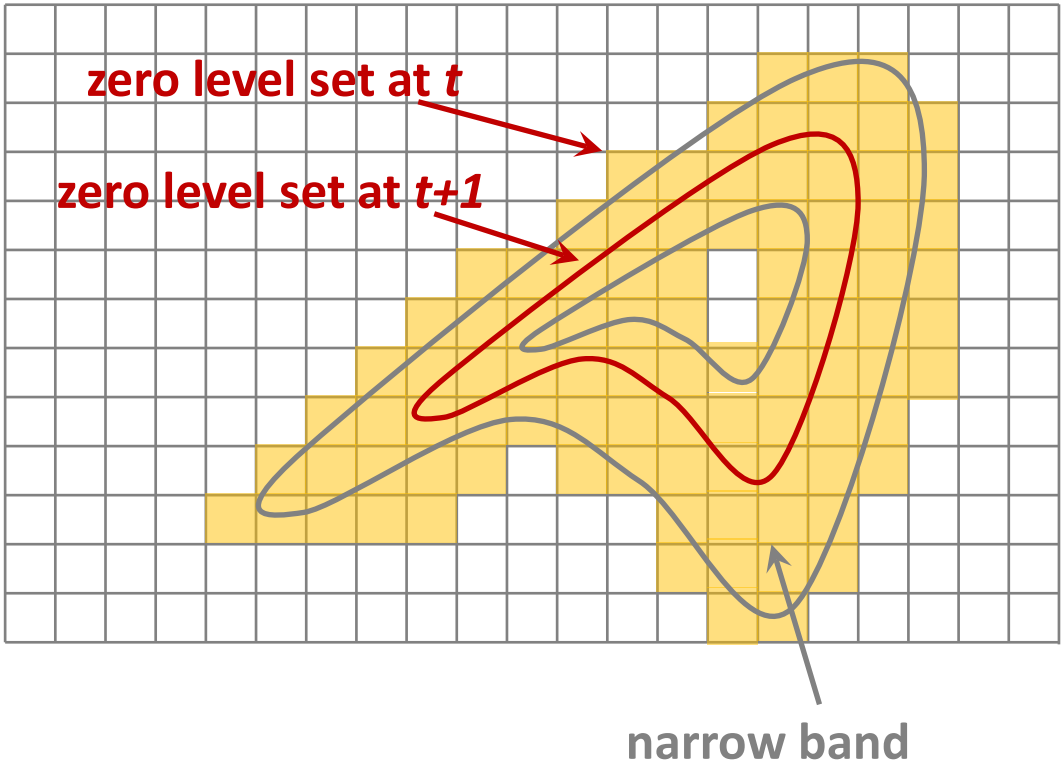

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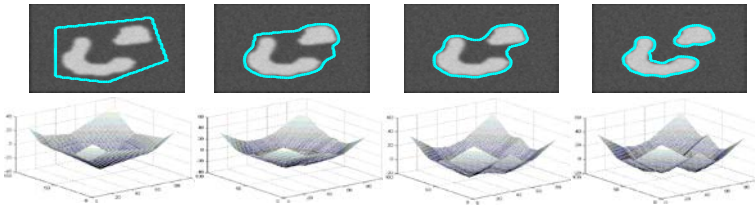

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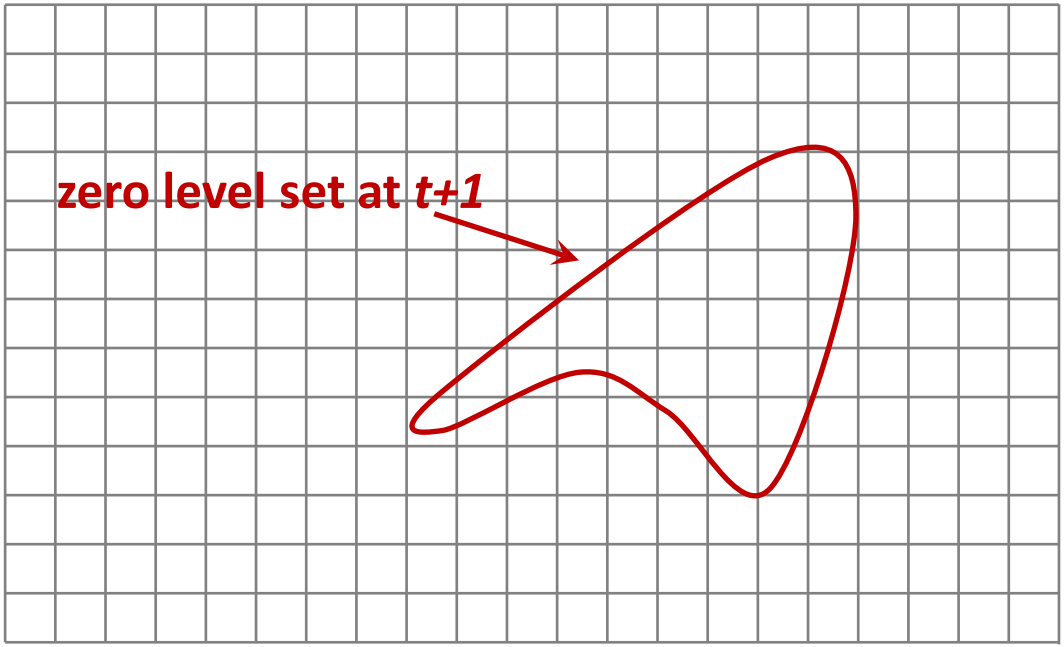

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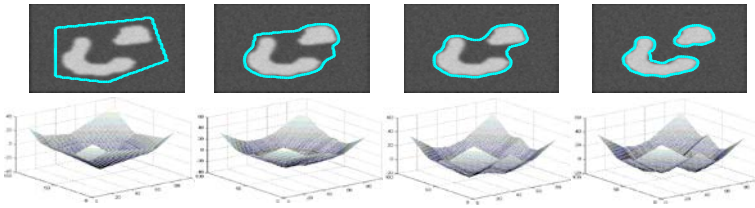

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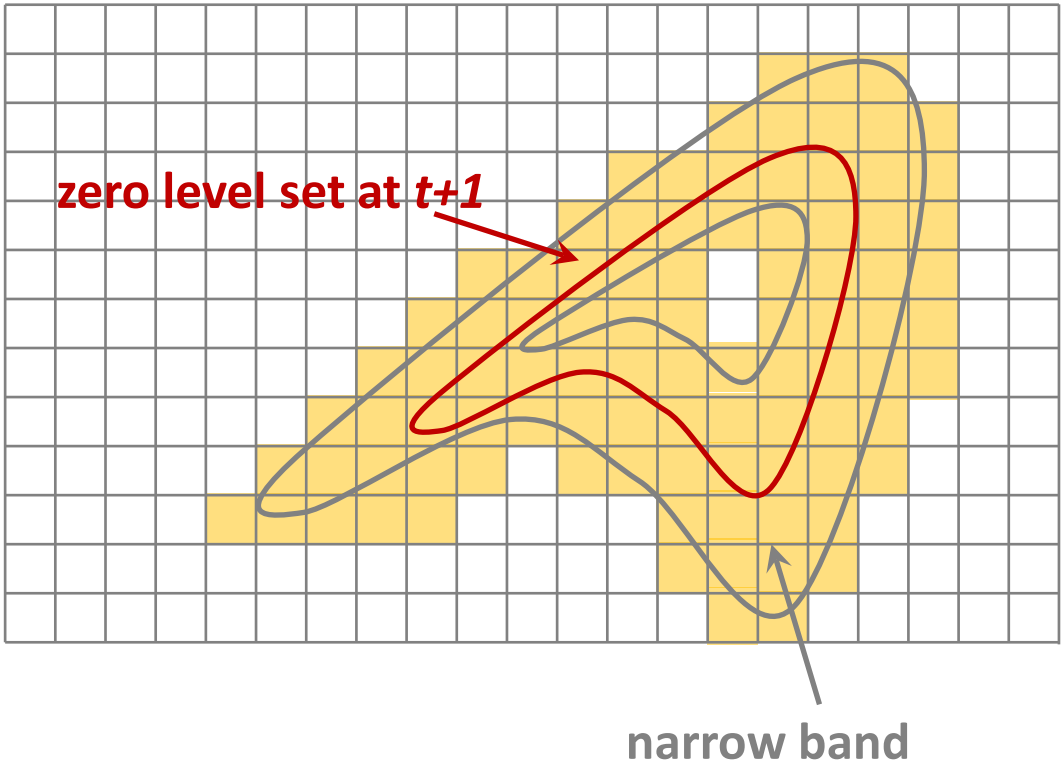

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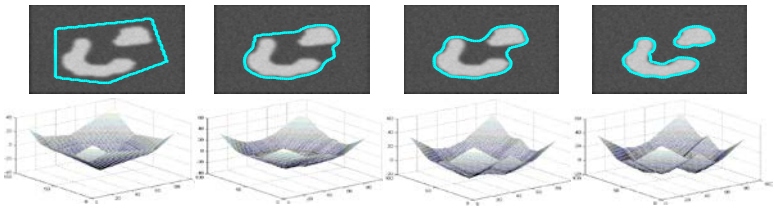

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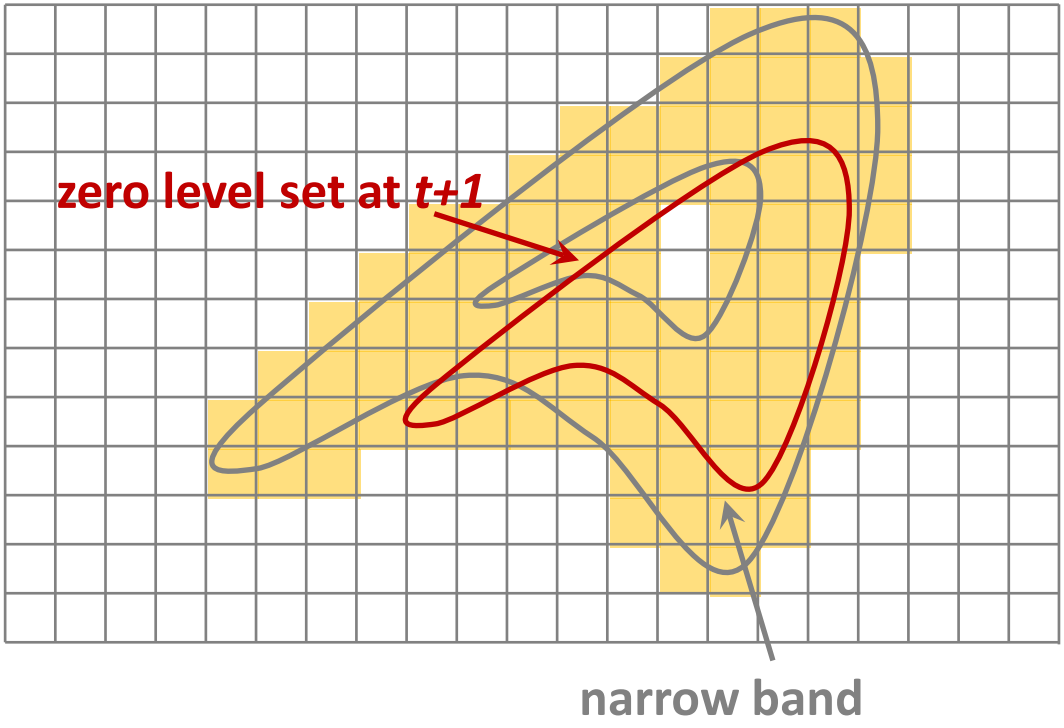

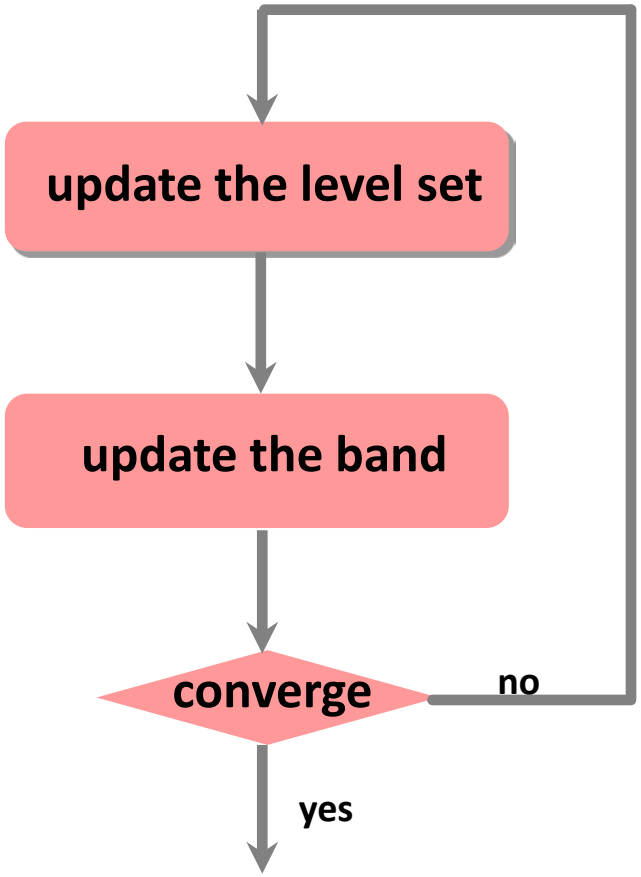

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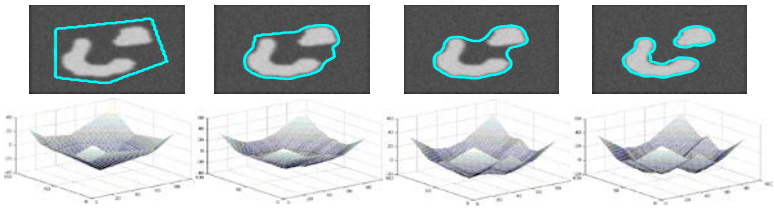

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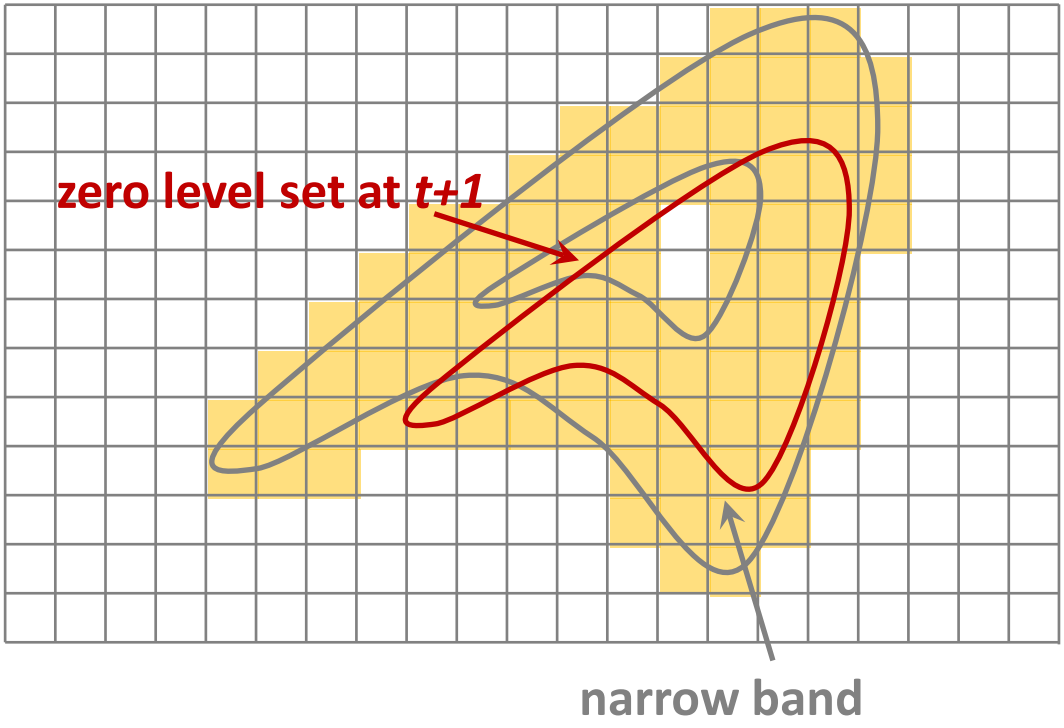
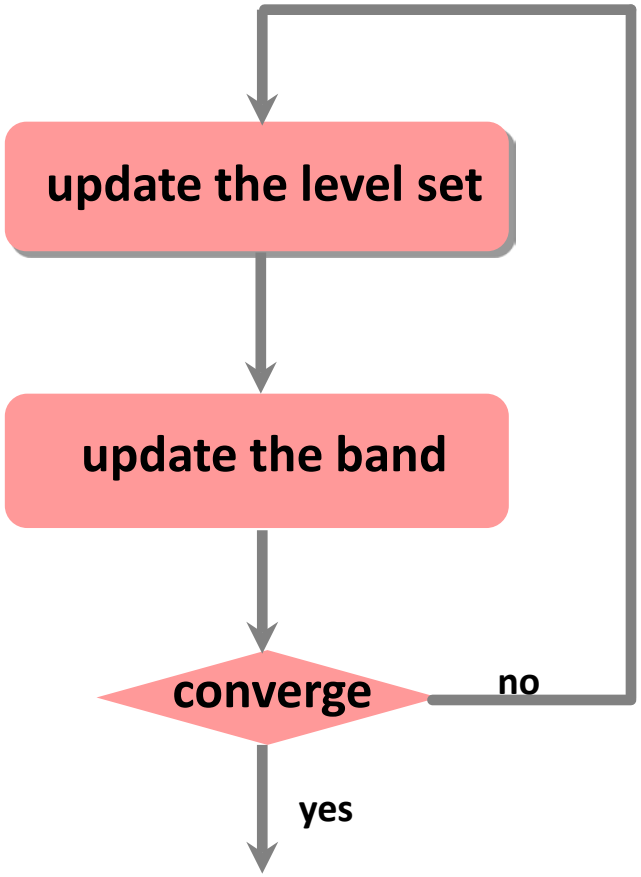
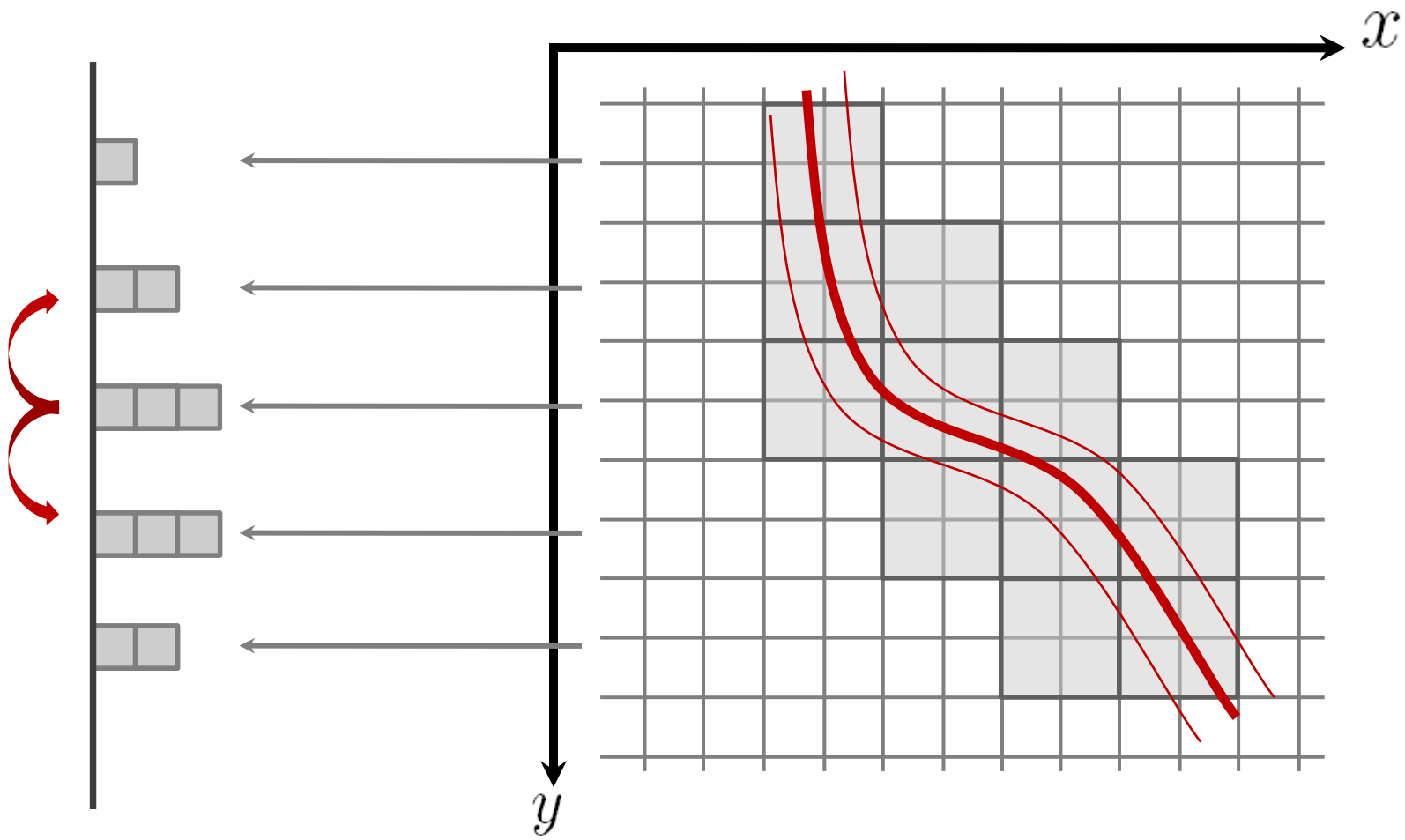
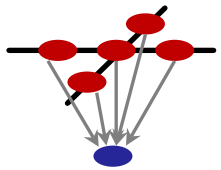




Autotuning parameter: narrow band width

Projection of Manifold into Dense Stencil

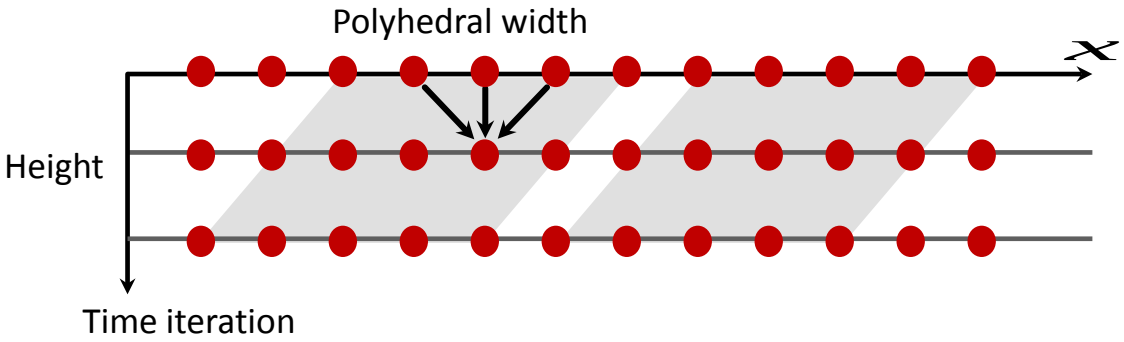




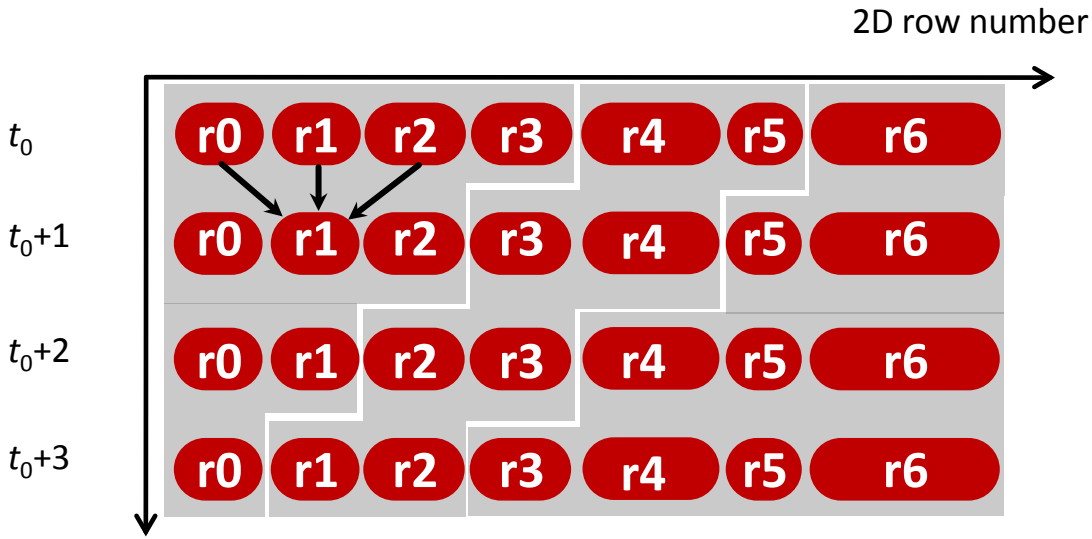
Autotuning parameter: tile size

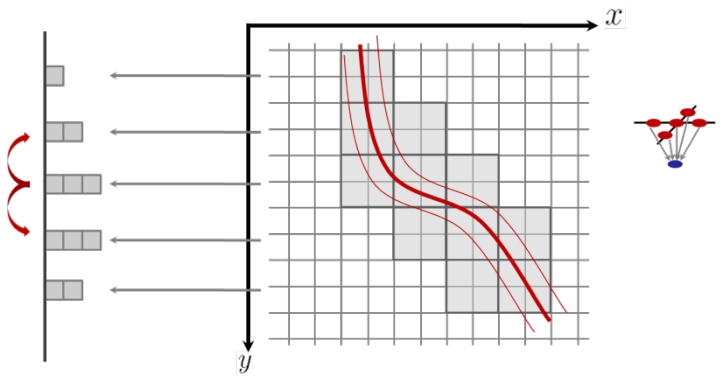
Projective Time Skewing

Standard 1-D dense time-skewing



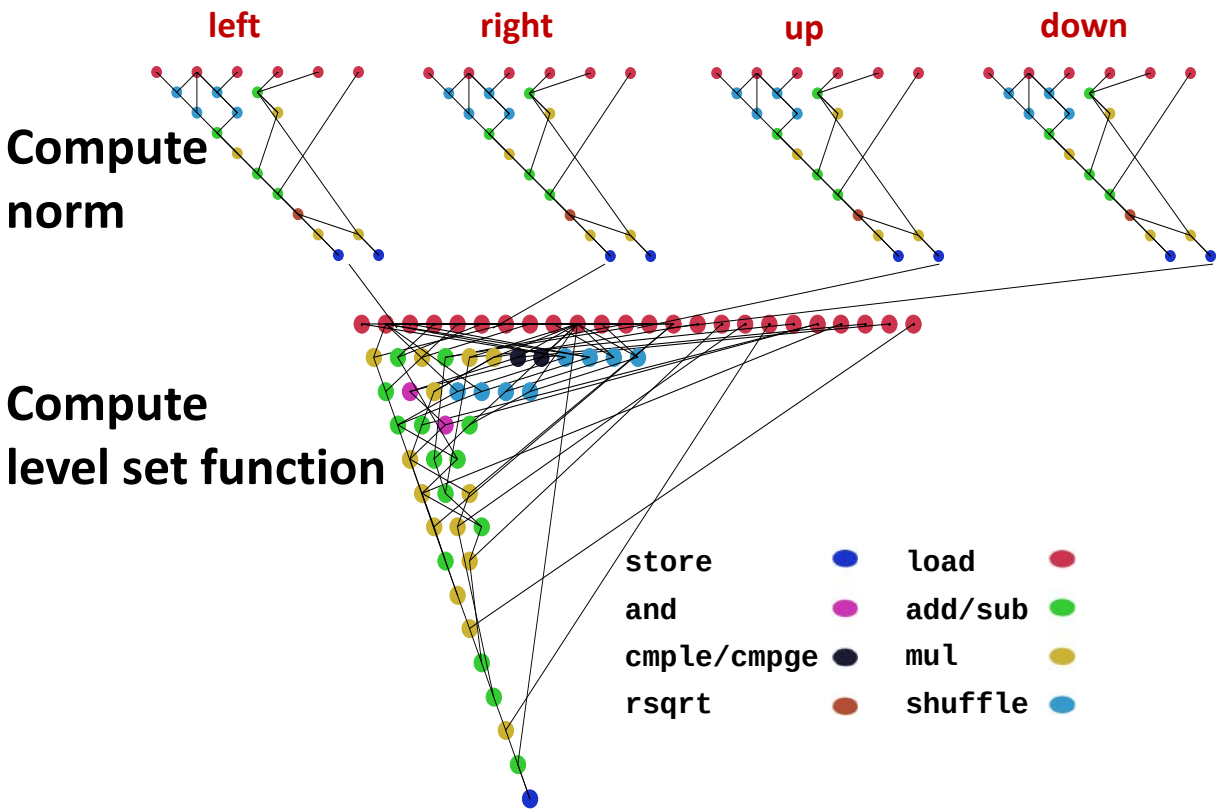
Projective time-skewing



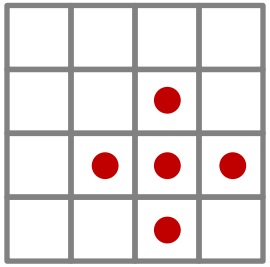


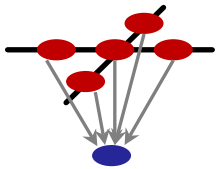
Autotuning parameter: polyhedral tile size

In-Core Stencil Optimization

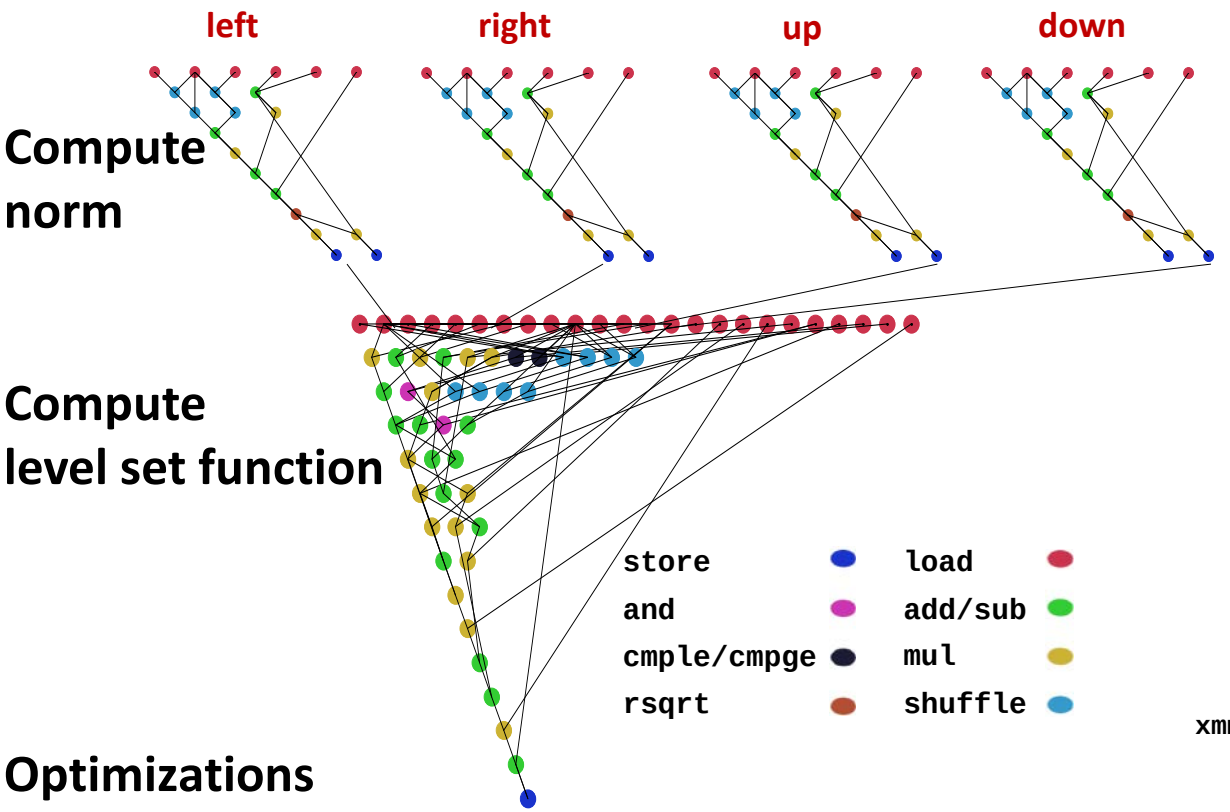


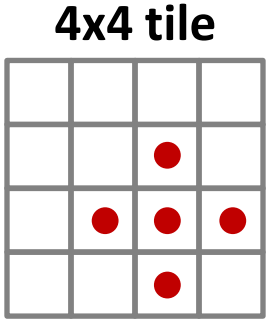
4x4 tile

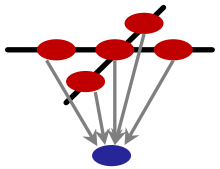


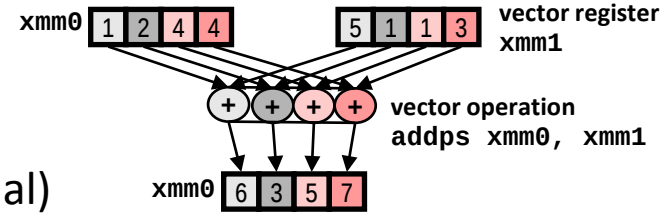


In-Core Stencil Optimization





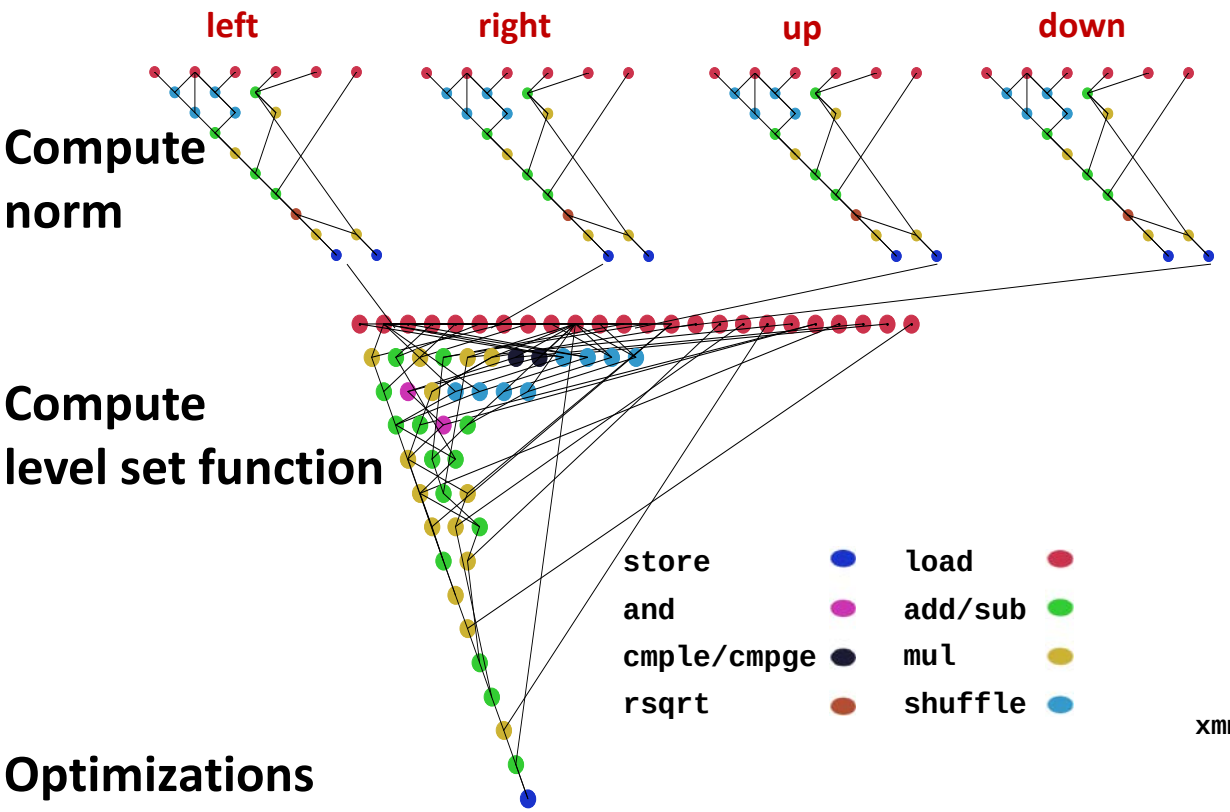


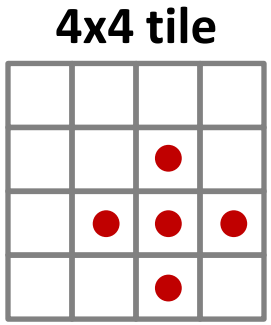


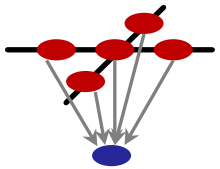
Optimizations

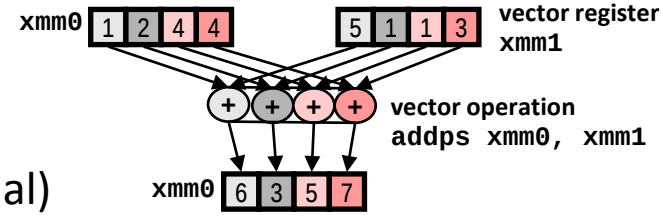
- Common subexpression elimination
- Transcendental function approximation (cos by polynomial)
- SIMD vectorization
- Instruction scheduling (intra and inter stencil)

In-Core Stencil Optimization







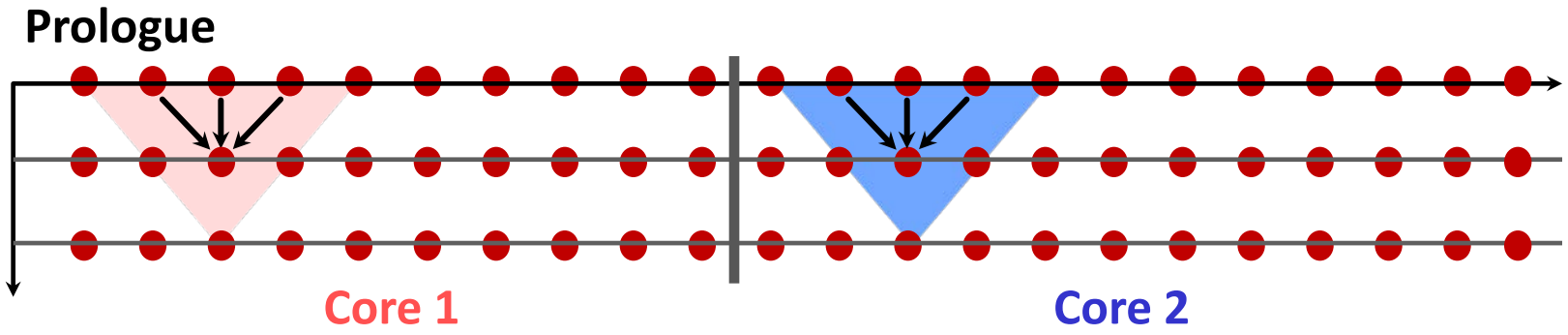


Optimizations

- Common subexpression elimination
- Transcendental function approximation (cos by polynomial)
- SIMD vectorization
- Instruction scheduling (intra and inter stencil)

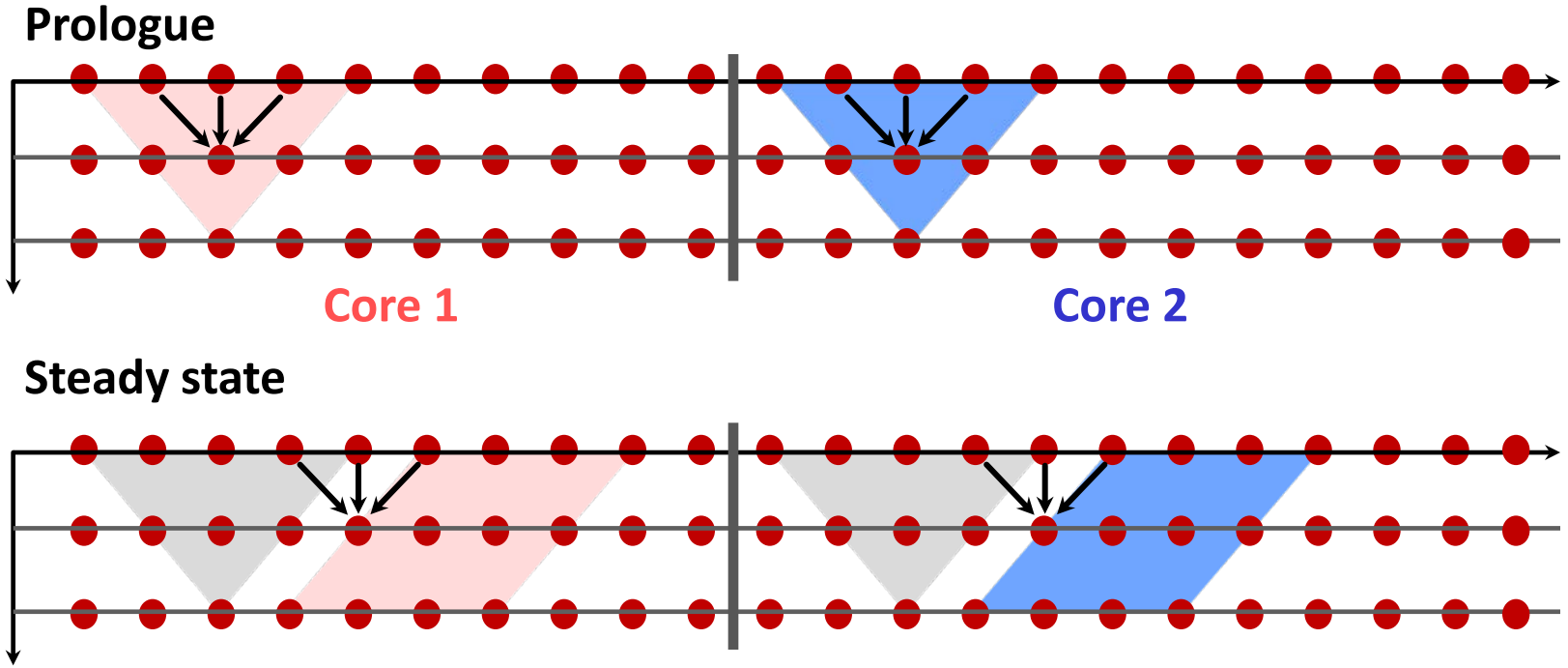
Autotuning parameter: tile instruction schedule

Multicore Optimization: Software Pipeline

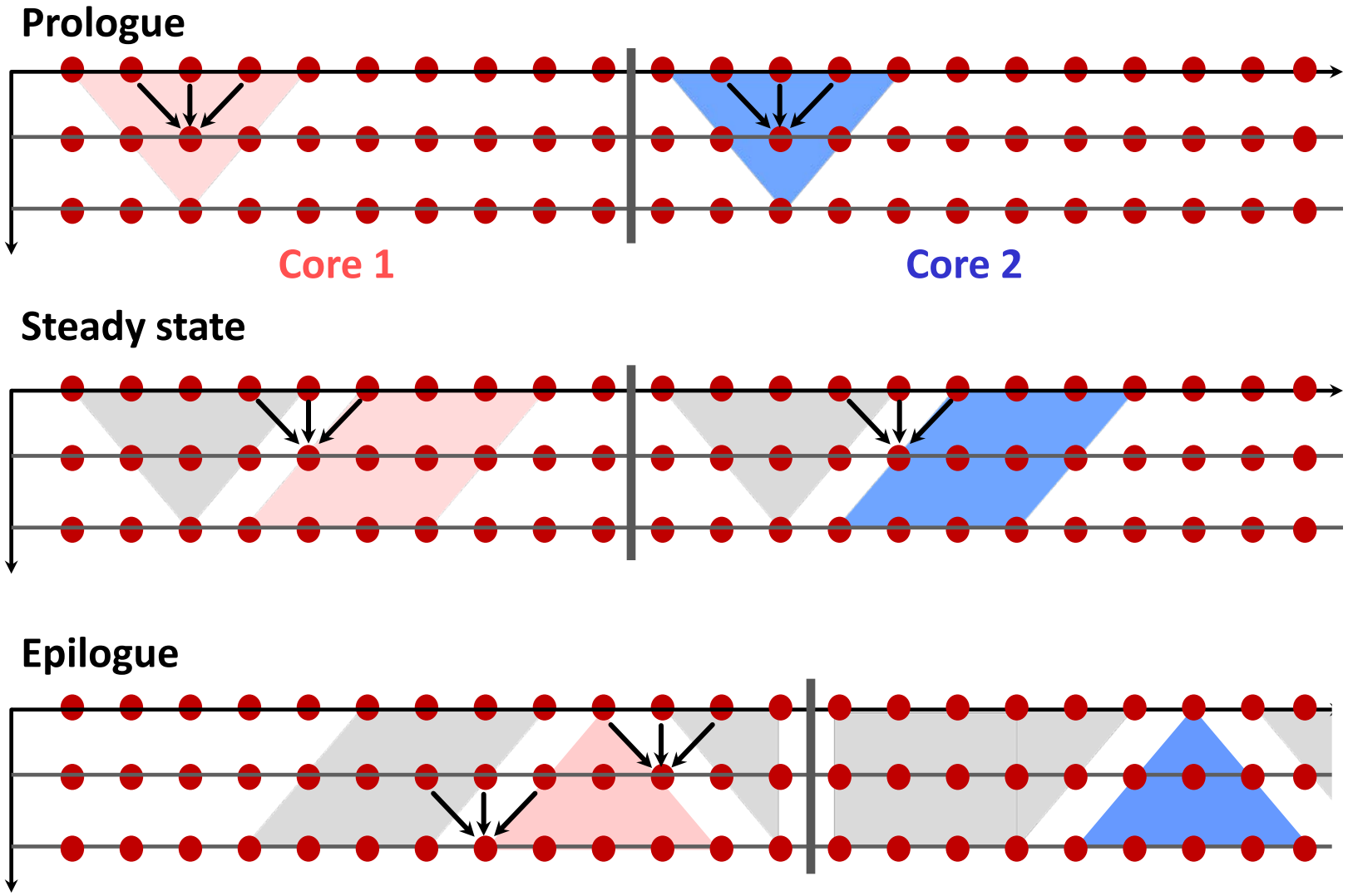


Autotuning parameter: prologue/epilogue vs. steady state

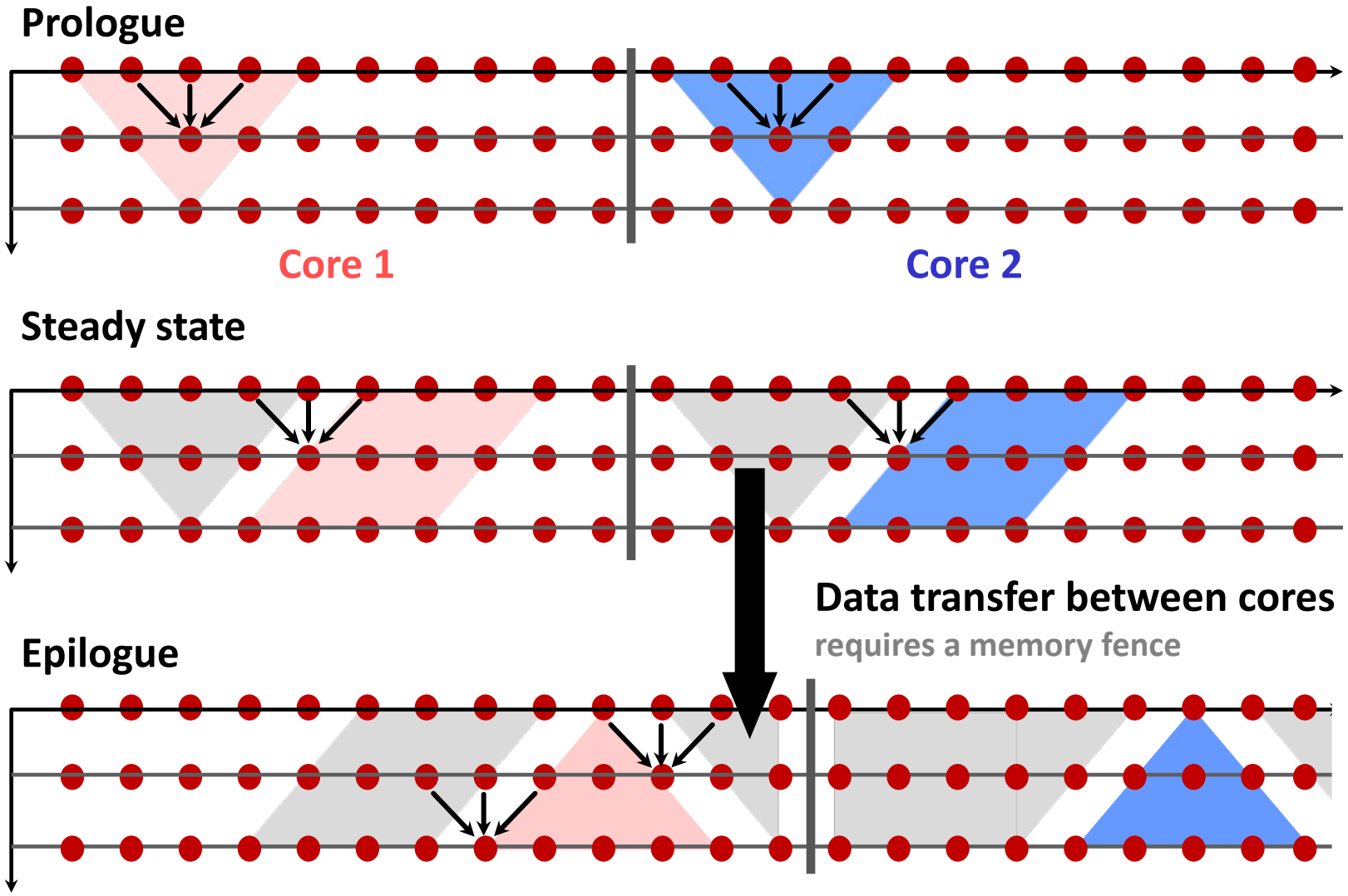
Multicore Optimization: Software Pipeline



Multicore Optimization: Software Pipeline

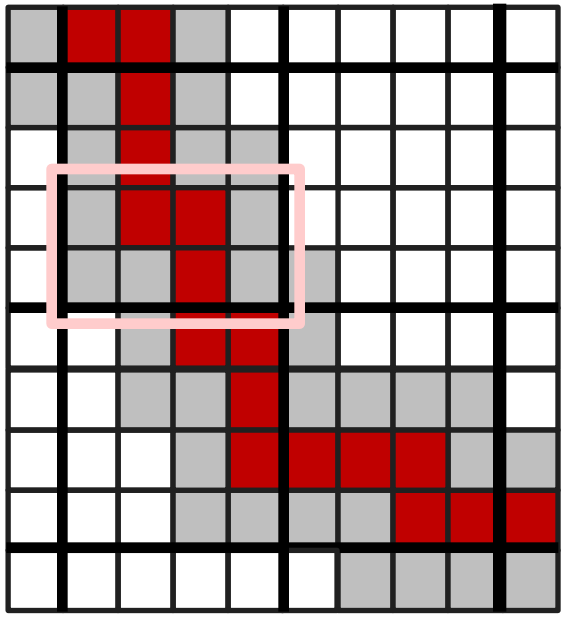


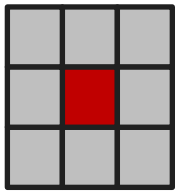
Multicore Optimization: Software Pipeline



Autotuning parameter: prologue/epilogue vs. steady state

Narrow Band Update: Program Generation

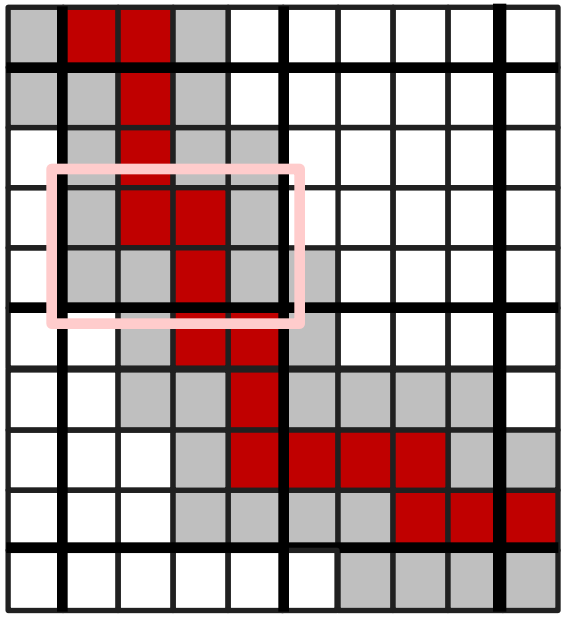


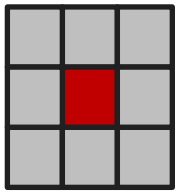


Rubber stamp

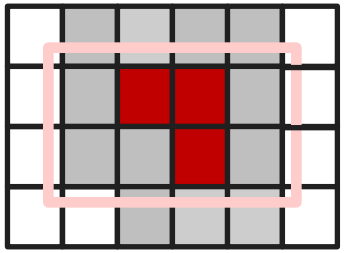
```
// rubber stamp zero level set
for (i=0;i<TILE;i++)
  for (j=0;j<TILE;j++)
    if (!is_zero(Ti+i,Tj+j)) {
      for (k=-BAND;k<=BAND;k++)
         for (m=-BAND;m<=BAND;m++)
           band[Ti+i+k][Tj+j+m]=1;
    }
```

Narrow Band Update: Program Generation





Rubber stamp

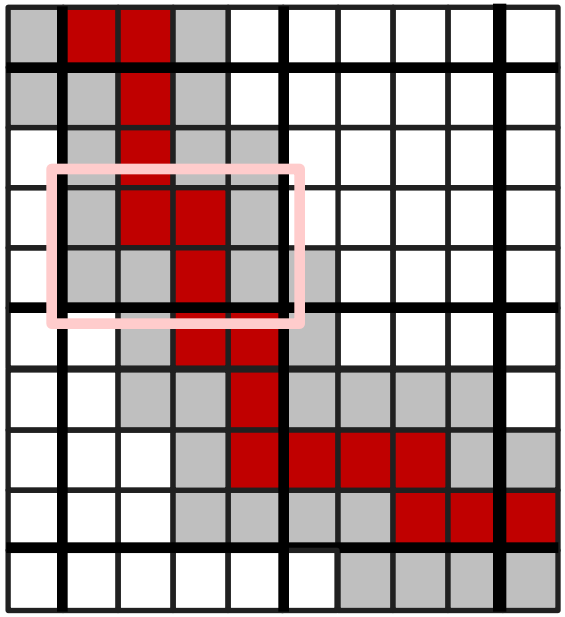


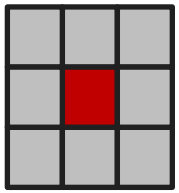
2x4 rubber stamp

```
// rubber stamp zero level set
for (i=0;i<TILE;i++)
  for (j=0;j<TILE;j++)
    if (!is_zero(Ti+i,Tj+j)) {
      for (k=-BAND;k<=BAND;k++)
         for (m=-BAND;m<=BAND;m++)
           band[Ti+i+k][Tj+j+m]=1;
    }
```

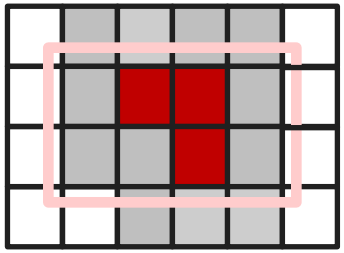
```
// TILE=4x4, BAND=+/-1
// unroll: 2x4
for (i=0;i<4;i+=2) {
  b0=&band[Ti+i-1][Tj-1];
  b1=&band[Ti+i][Tj-1];
  b2=&band[Ti+i+1][Tj-1];
  b3=&band[Ti+i+2][Tj-1];
  switch (zeropat(Ti+i,Tj)) {
    ...
    case PAT(0,1,1,0
             0,0,1,0):
      b0[1]=1;b0[2]=1;b0[3]=1;b0[4]=1;
      b1[1]=1;b1[2]=1;b1[3]=1;b1[4]=1;
      b2[1]=1;b2[2]=1;b2[3]=1;b2[4]=1;
      b3[2]=1;b3[3]=1;b2[4]=1;
      break;
    case PAT(...):
}
```

Narrow Band Update: Program Generation





Rubber stamp



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  b2=&band[Ti+i+1][Tj-1];
  b3=&band[Ti+i+2][Tj-1];
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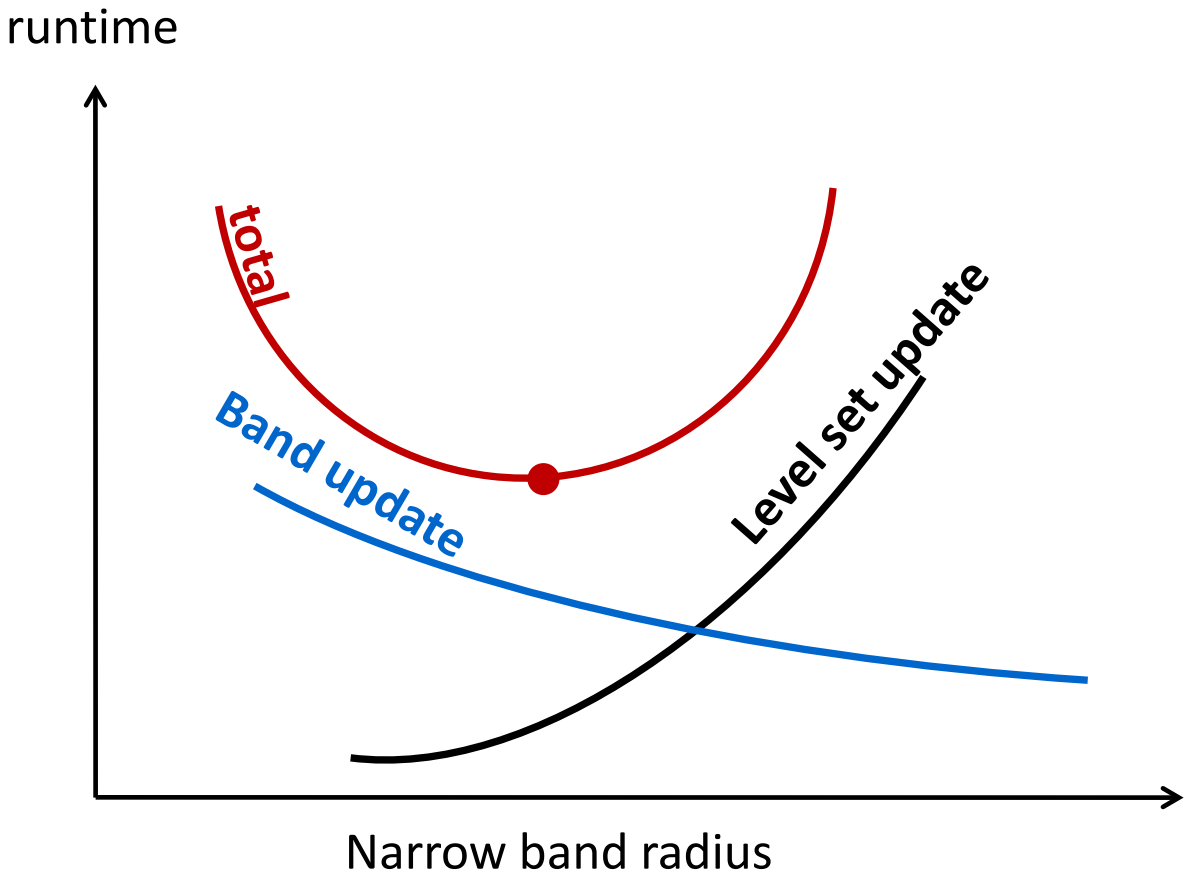
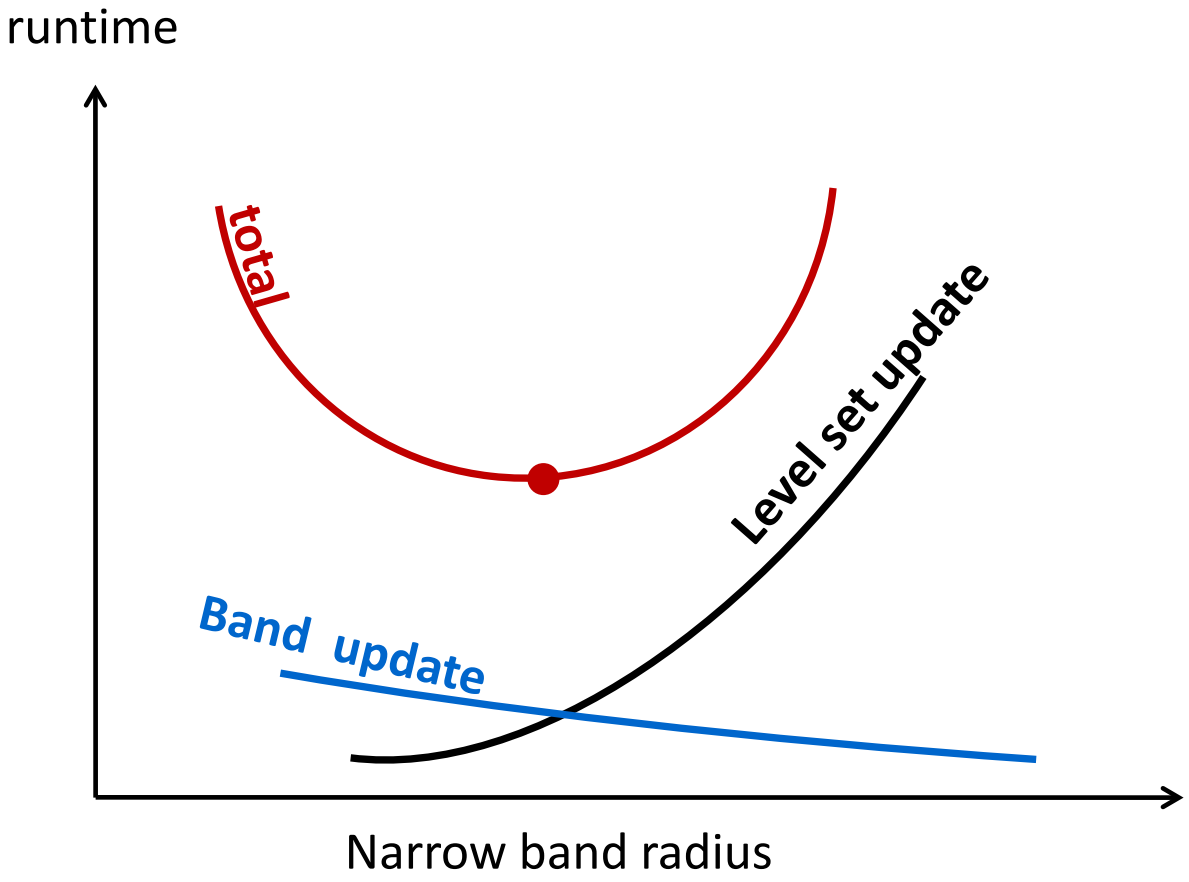
    case PAT(0,1,1,0
             0,0,1,0):
      b0[1]=1;b0[2]=1;b0[3]=1;b0[4]=1;
      b1[1]=1;b1[2]=1;b1[3]=1;b1[4]=1;
      b2[1]=1;b2[2]=1;b2[3]=1;b2[4]=1;
      b3[2]=1;b3[3]=1;b2[4]=1;
      break;
    case PAT(...):
}
```

Autotuning parameter: rubber stamp unrolling

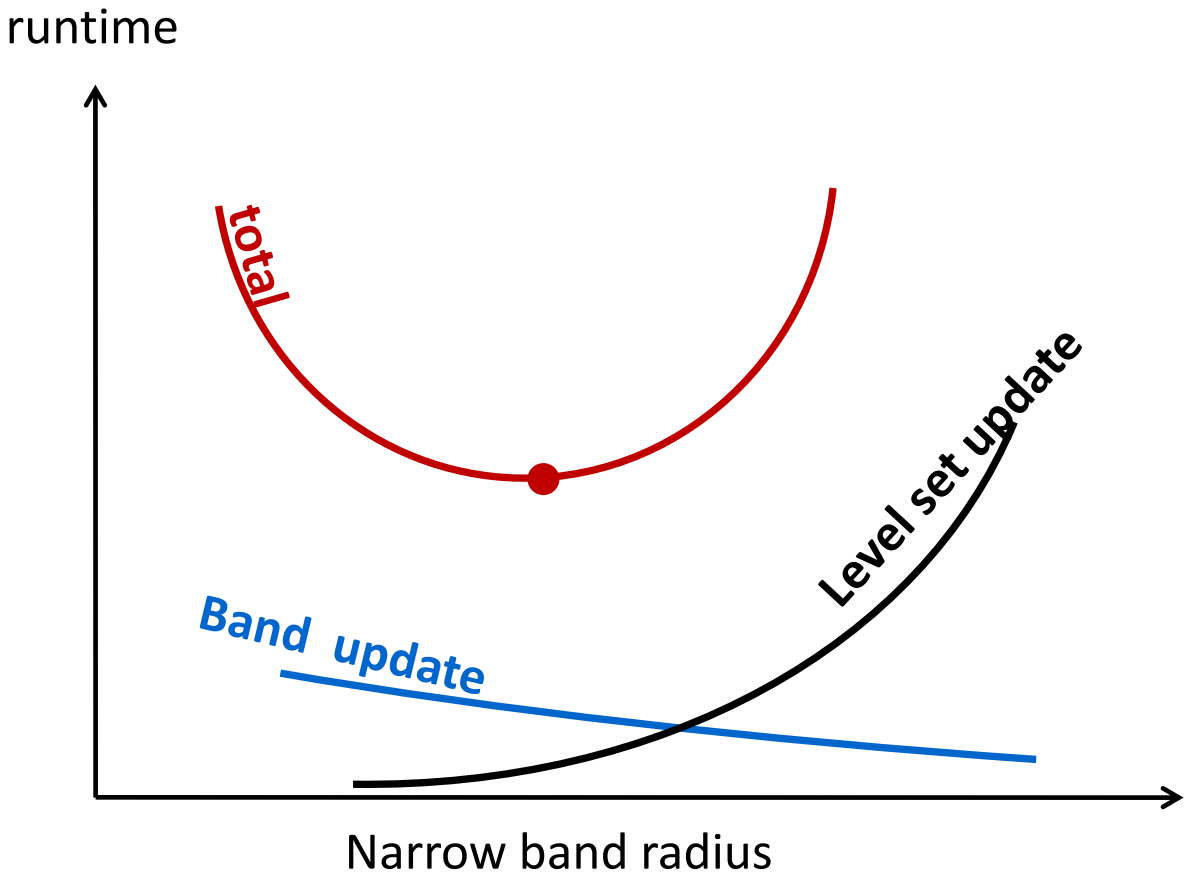
A Fundamental Tradeoff



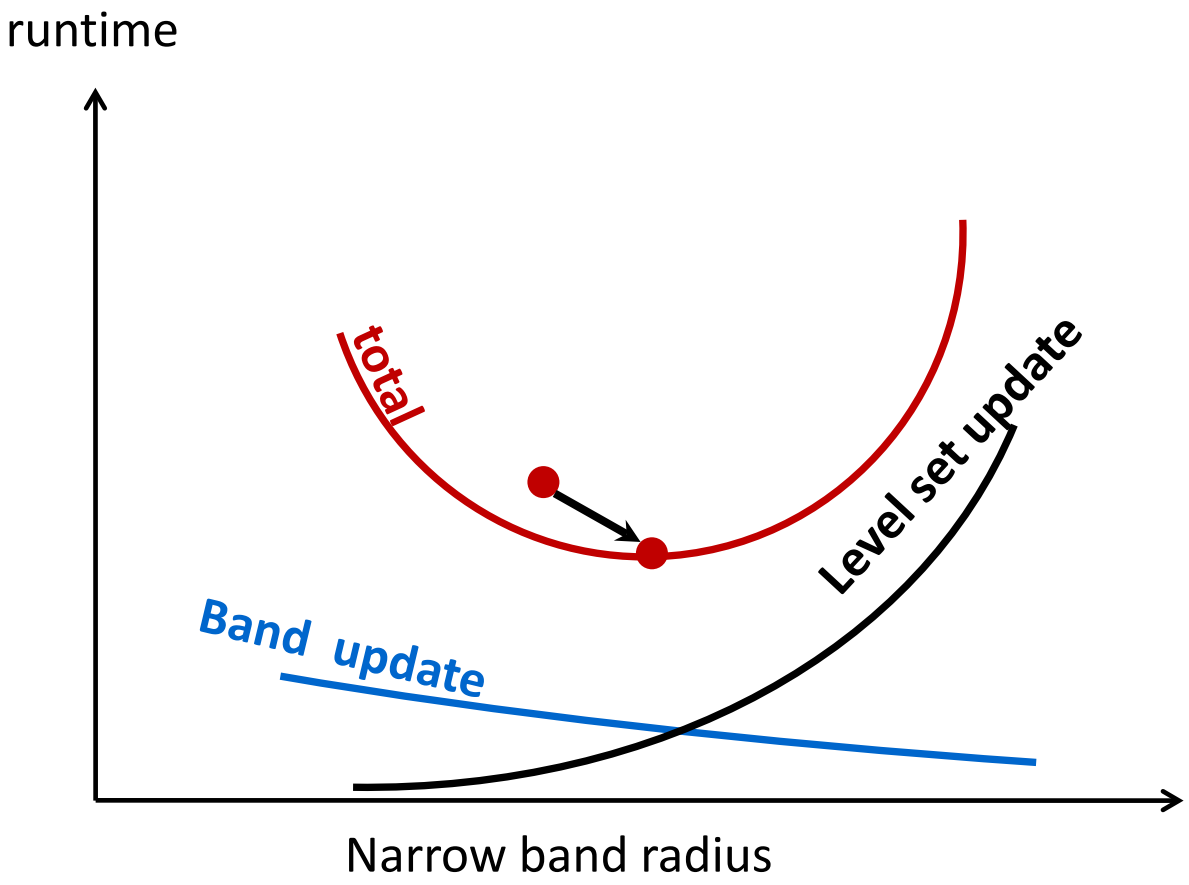
A Fundamental Tradeoff



A Fundamental Tradeoff



A Fundamental Tradeoff



Parameter Space

Tuning Parameters	Range
Tile size	{1,2,4,8}x{4,8,16}
Band radius	{1,2,3,4,5,6,7,8}
Polytope size height	{2, 4, 8, 16, 24, 32, 48, 64, 80, 96, 128, 160, 192}
Polytope size height	{2, 4, 8, 12, 16, 32}
Enable/disable	SIMD, instruction scheduling, approx. cos(), padding, large pages,…

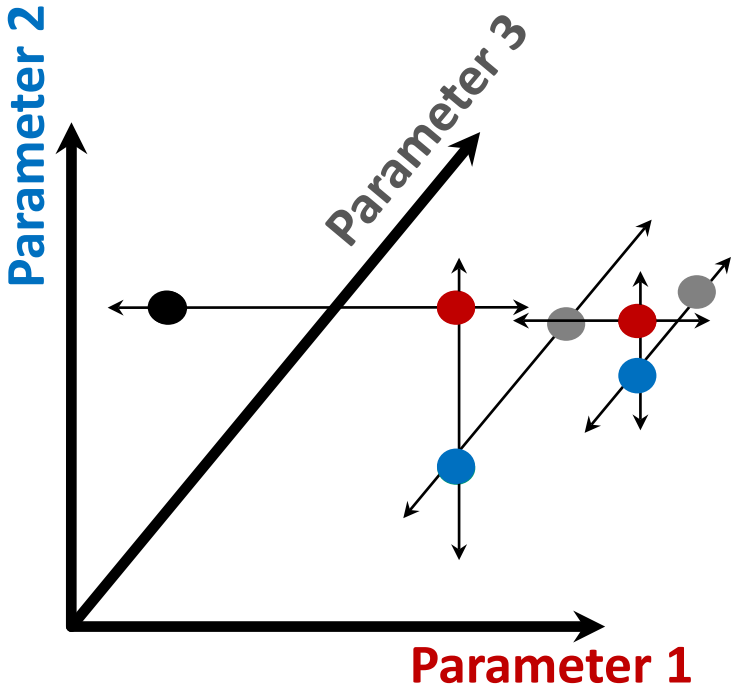
Autotuning: Iterative Line Search

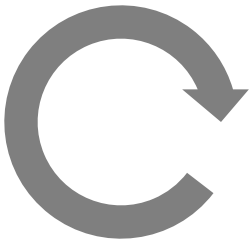
Iterative Line search

- Search parameters one by one hold others fixed
- Multiple refinement iterations
- Search space is well-behaved

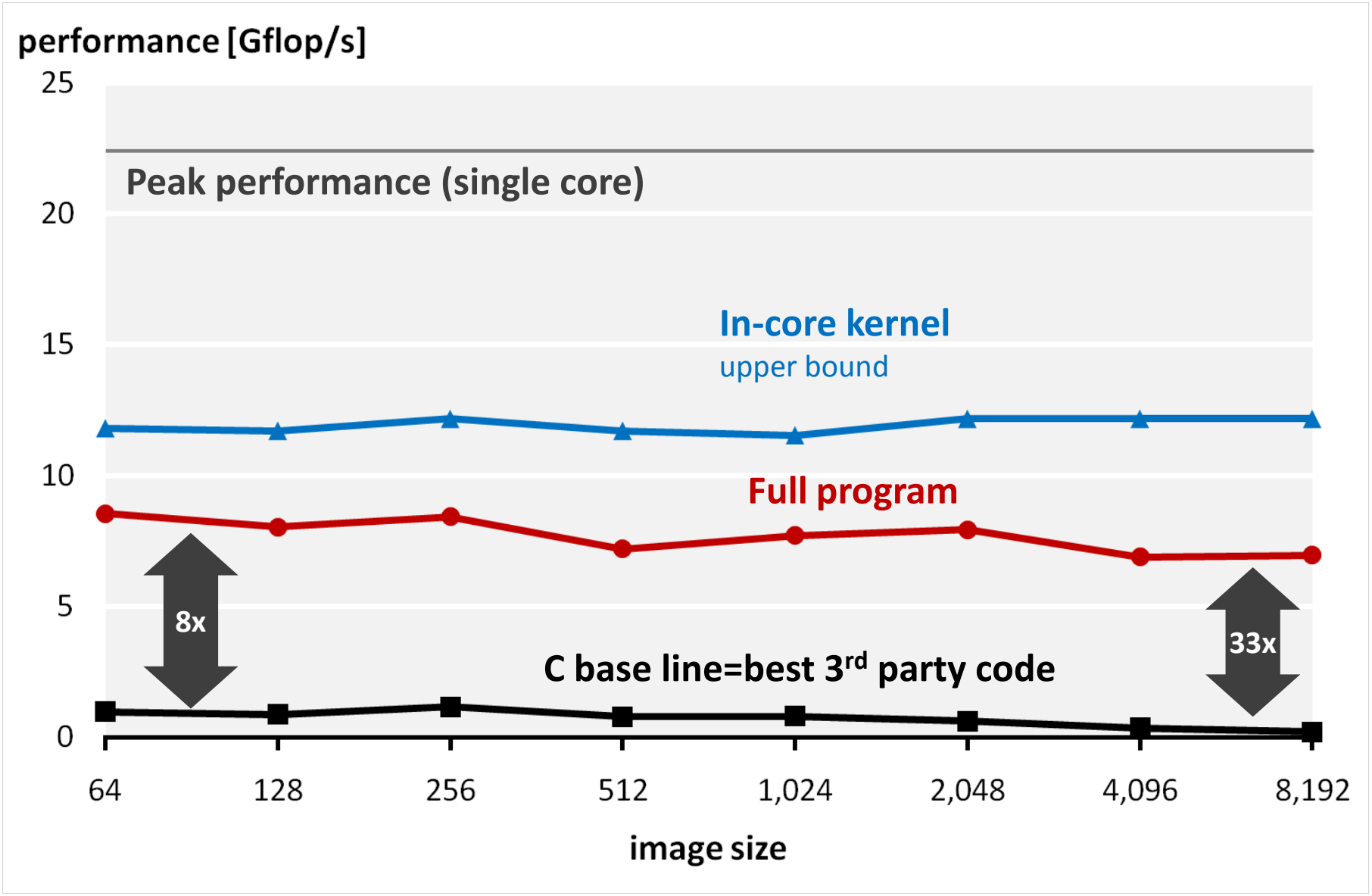
Heuristics

- Cut search space
- For instance: DAG scheduling

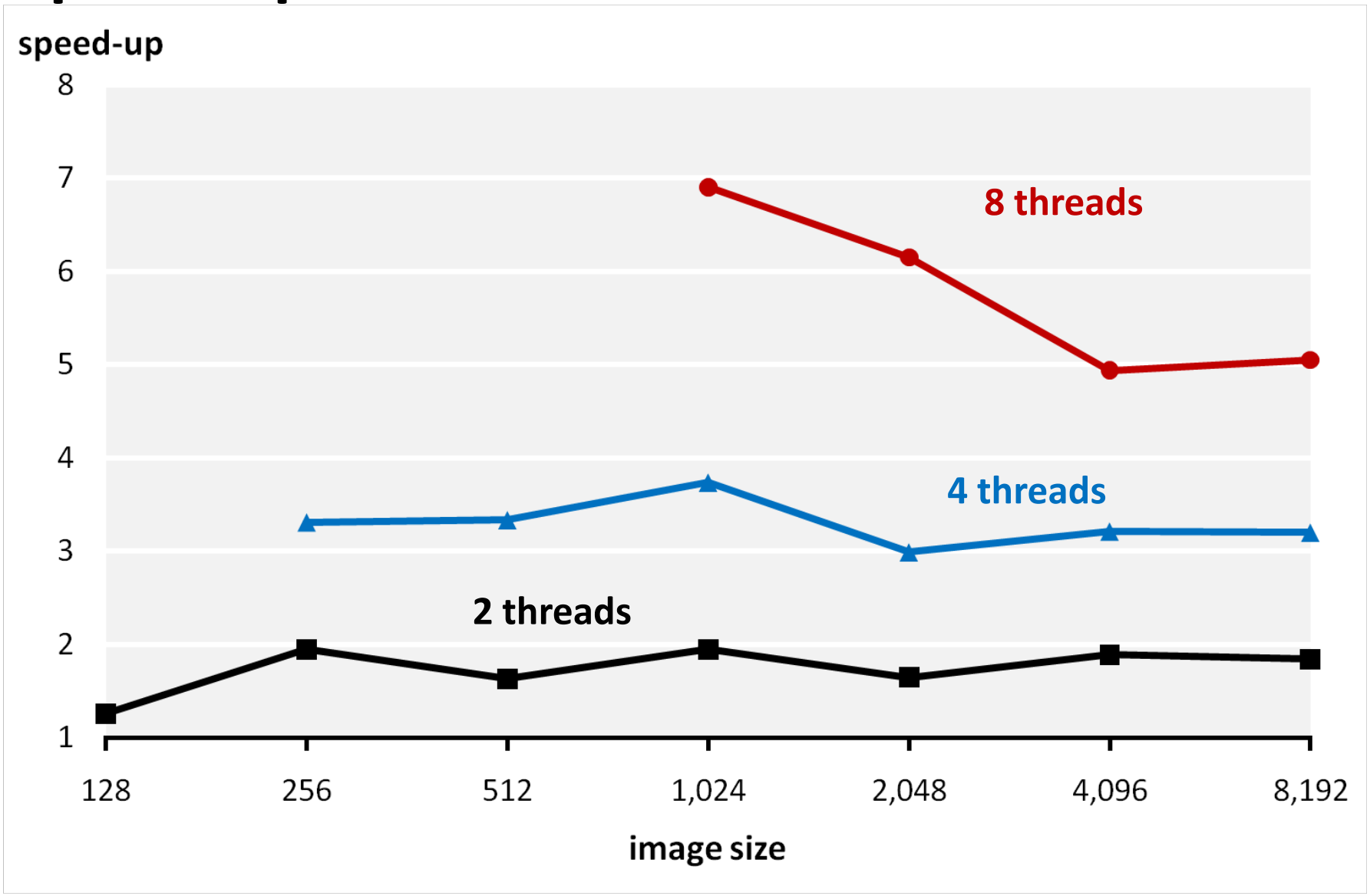




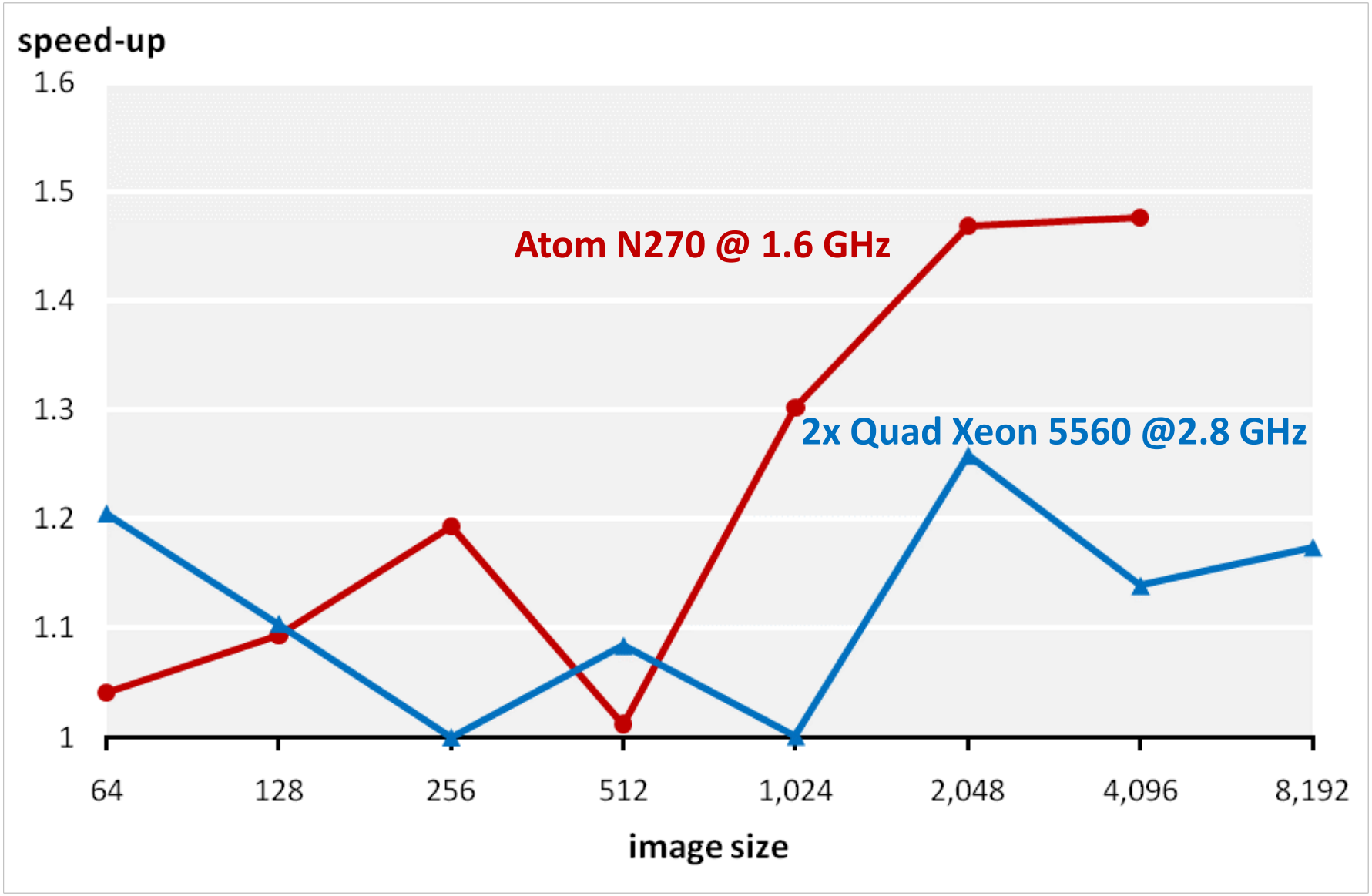
Efficiency on Single Core 2.8 GHz Xeon 5560



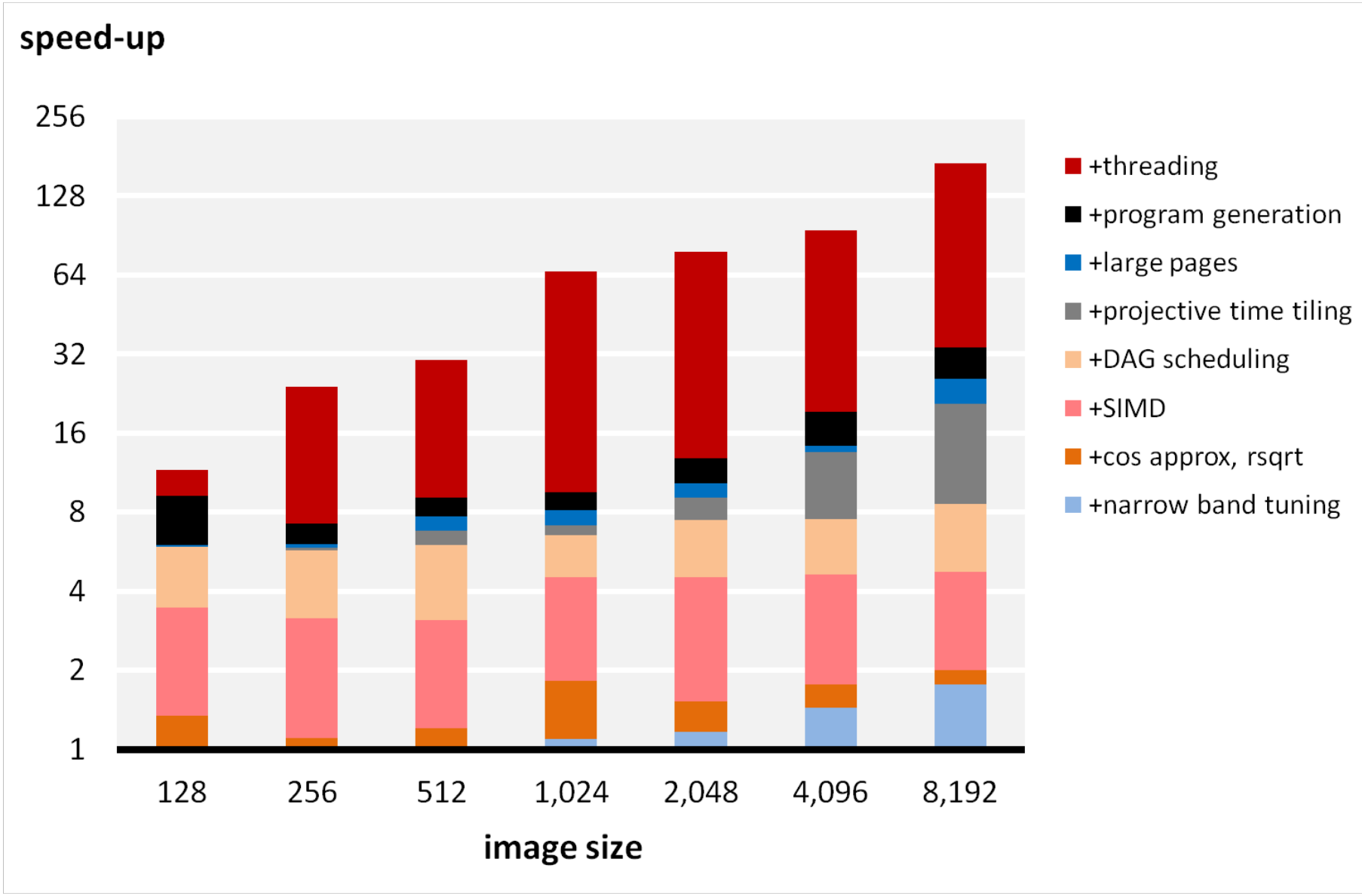
Speed-Up On 2x 2.8 GHz Quad Xeon 5560



Performance Gain Through Autotuning



Speedup Breakdown on 2x Xeon 5560



Lessons From Optimizing Level Set

- **10x to 100x speed-up is often possible**
  really hard work, specific to the problem
- **Doable with standard tools**
  C compiler, autotuning, and program generation scripts
- **Crucial: extract meaningful parameters**
  capture machine/algorithm interaction, one algorithm a time
- **Many things must be done right**
  SIMD, threading, low-level tricks, specialization, tuning
- **Autotuning gives the last 50% to 2x speed-up**
  the remaining 5x to 50x come from standard optimization

More Information:

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