Languages for High-Performance Computing

CSE 501

Spring 15

Announcements

- Homework 1 due next Monday at 11pm
  - Submit your code on dropbox
- Andre will have office hours today at 2:30 in CSE 615
- Project midpoint report due on May 5

Course Outline

- Static analysis
- Language design
  - High-performance computing ← We are here
  - Parallel programming
  - Dynamic languages
- Program Verification
- Dynamic analysis
- New compilers

Today

- High-performance computing
- Languages for writing HPC applications
  - What are the design issues?
- Implementations of HPC languages
  - Using stencils as an example

Making Everything Easier!™

Sun and AMD Special Edition

High Performance Computing

FOR DUMMIES®

Learn to:

- Pick out hardware and software
- Find the best vendor to work with
- Get your people up to speed on HPC

Sun microsystems

AMD

High Performance Computing

- Application domains
  - Physical simulations
    - Heat equation, geo-modeling, traffic simulations
  - Scientific computations
    - Genomics, physics, astronomy, weather forecast, …
  - Graphics
    - Rendering scenes from movies
  - Finance
    - High-frequency trading

High Performance Computing

- Hardware characteristics
  - Dedicated clusters of compute and storage nodes
  - Compute nodes:
    - Ultra-fast CPUs
    - Large cache
  - Dedicated interconnect network
    - Nodes arranged in a torus / ring
  - Separated physical storage from compute nodes

Example: Titan

- Built by Cray
- 18688 AMD 16-core CPUs, Tesla GPUs
- 8.2MW
- 4352 Ft^2
- 693.5 TB memory
- 40 PB disk storage
- 17.59 P-FLOPS
- $97 million

Not your typical desktop machine

How to program HPC clusters?

- Highly (embarrassingly) parallel programs
  - Fortran, C, C++
  - Now using high performance DSLs
- Utilize both GPU and CPUs
- Batch job submission model

- Goal: utilize as many cores at the same time as possible

Stencil Programs

Stencils Programs

- **Definition**: For a given point, a ***stencil*** is a fixed subset of nearby neighbors.

- A ***stencil code*** updates every point in an d-dimensional spatial grid at time t as a function of nearby grid points at times `t−1`, `t−2`, …, `t−k`, for T time steps.

- Used in iterative PDE solvers such as Jacobi, multigrid, and adaptive mesh refinement, as well as for image processing and geometric modeling.

Stencil Programs

- Discretize space and time
- Typical program structure:

```
for (t = 0; t < MAX_TS; ++t) {
  for (x = 0; x < MAX_X; ++x) {
    for (y = 0; y < MAX_Y; ++y) {
      array[t, x, y] =
        f(array[t-1, x, y], array[t-1, x-1, y-1], …);
     }
  }
}
```

Stencil Programs

- Some terminology:
  - A stencil that updates a given point using N nearby neighbor points is called a N-point stencil
  - The computation performed for each stencil is called a kernel
  - Boundary conditions describe what happens at the edge of the grid
    - Periodic means that the edge wraps around in a torus

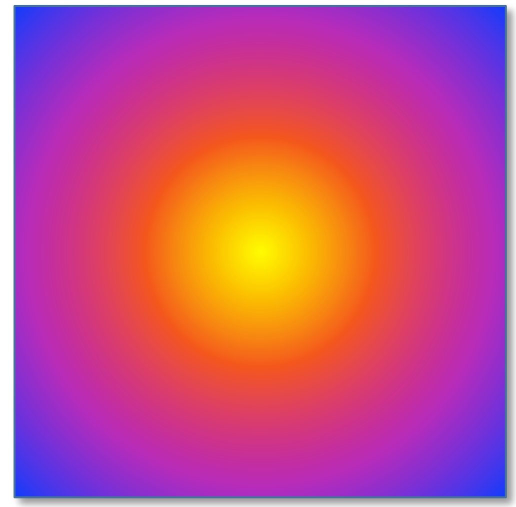
Example: 2D Heat Diffusion

Let `a[t,x,y]` be the temperature at time `t` at point `(x,y)`.

Heat equation

$$\frac{\partial a}{\partial t} = \alpha\left(\frac{\partial^2 a}{\partial x^2} + \frac{\partial^2 a}{\partial y^2}\right)$$

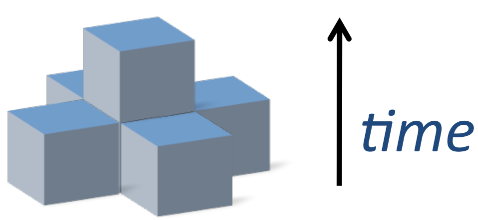
α is the ***thermal diffusivity***.

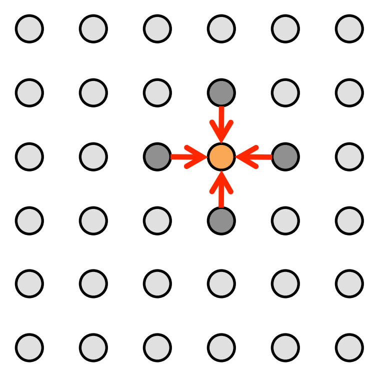


Update rule

```
a[t,x,y] = a[t–1,x,y]
           + CX·(a[t–1,x+1,y] - 2·a[t–1,x,y] + a[t–1,x–1,y)]
           + CY·(a[t–1,x,y+1] - 2·a[t–1,x,y] + a[t–1,x,y–1)]
```

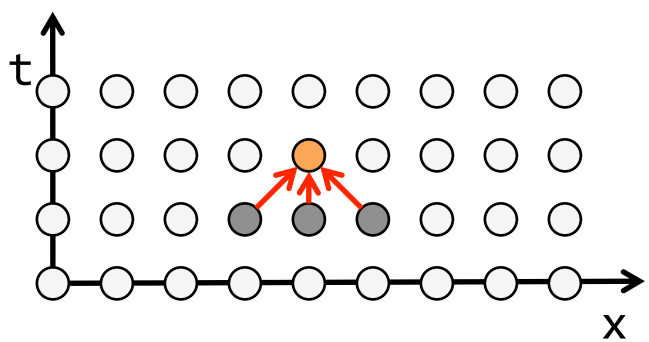
2D 5-point stencil



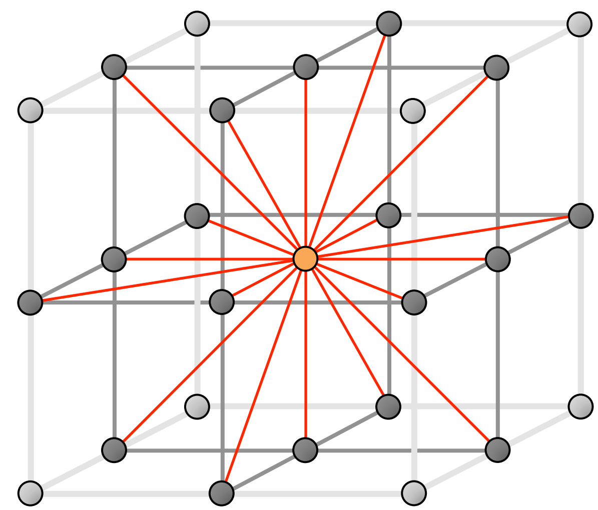


More Examples

1D 3-point stencil



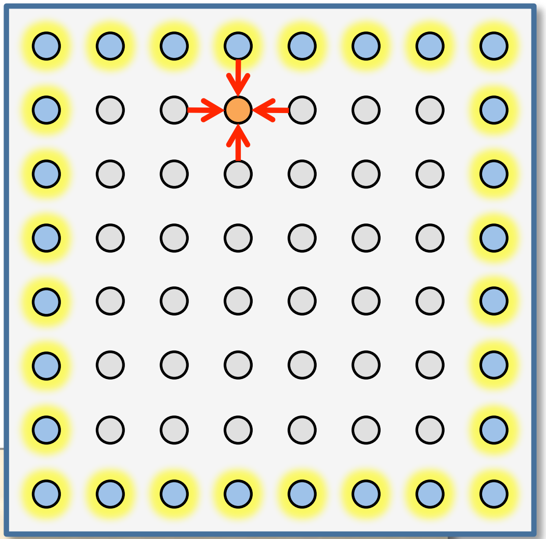
3D 19-point stencil



Classical Looping Implementation

Implementation tricks

- Reuse storage for even and odd time steps.
- Keep a ***halo*** of ***ghost cells*** around the array with boundary values.



```
for (t = 1; t <= T; ++t) {
  for (x = 0; x < X; ++x) {
    for (y = 0; y < Y; ++y) { // do stencil kernel
      a[t%2, x, y]
          = a[(t-1)%2, x, y]
            + CX*(a[(t-1)%2, x+1, y] - 2.0*a[(t-1)%2, x, y]
                  + a[(t-1)%2, x-1, y)]
            + CY*(a[(t-1)%2, x, y+1] - 2.0*a[(t-1)%2, x, y]
                  + a[(t-1)%2, x, y-1)];
} } }
```

Conventional cache optimization: *loop tiling*.

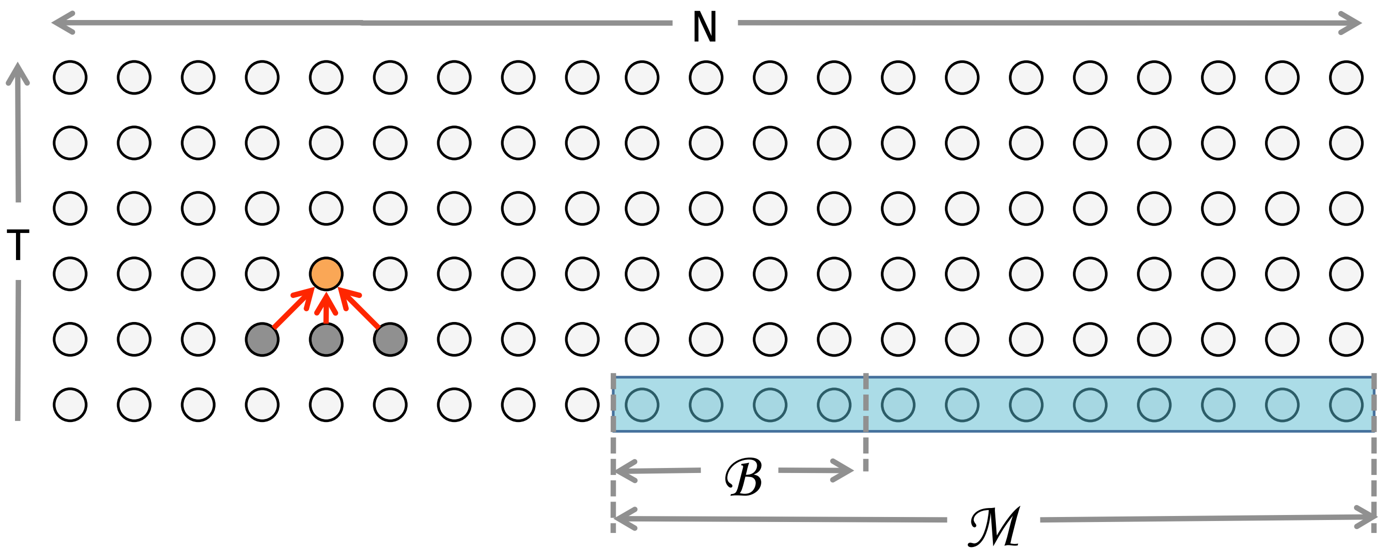
Parallelizing Loops

```
for (t = 1; t <= T; ++t) {
  cilk_for (x = 0; x < X; ++x) {
    cilk_for (y = 0; y < Y; ++y) { // do stencil kernel
      a[t%2, x, y]
          = a[(t-1)%2, x, y]
            + CX*(a[(t-1)%2, x+1, y] - 2.0*a[(t-1)%2, x, y]
                        + a[(t-1)%2, x-1, y)]
            + CY*(a[(t-1)%2, x, y+1] - 2.0*a[(t-1)%2, x, y]
                        + a[(t-1)%2, x, y-1)];
} } }
```

- All the iterations of the spatial loops are independent and can be parallelized straightforwardly.
- Intel Cilk Plus provides a `cilk_for` construct that performs the parallelization automatically.
- OpenMP is another framework for doing this

Issues with Looping

Example: 1D 3-point stencil



Issue: Looping is memory intensive and uses caches poorly. Assuming data-set size N, cache-block size $\mathcal{B}$, and cache size $\mathcal{M} <$ N, the number of cache misses for T time steps is $\Theta(NT/\mathcal{B})$.

Cache-Oblivious Stencil Code

Divide-and-conquer ***cache-oblivious*** techniques, based on ***trapezoidal decompositions***, are asymptotically efficient, achieving $\Theta(NT/\mathcal{MB})$ cache misses.

```
void trapezoid(int t0, int t1, int x0, int dx0, int x1, int dx1) {
  lt = t1 - t0;
  if (2 * (x1 - x0) + (dx1 - dx0) * lt >= 4 * lt) {
    int xm = (2 * (x0 + x1) + (2 + dx0 + dx1) * lt) / 4;
    trapezoid(t0, t1, x0, dx0, xm, -1);
    trapezoid(t0, t1, xm, -1, x1, dx1);
  } else if (lt > 1) {
      int halflt = lt / 2;
      trapezoid(t0, t0 + halflt, x0, dx0, x1, dx1);
      trapezoid(t0 + halflt, t1, x0 + dx0 * halflt, dx0, x1 + dx1 * halflt, dx1);
  } else {
      for (int t = t0; t < t1; ++t) {
        for (int x = x0; x < x1; ++x)
          kernel(t, x);
      x0 += dx0;
      x1 += dx1;
} }   }
```

1-dimensional trapezoidal-decomposition stencil code

Do you want to write this code?

Pochoir Stencil Compiler

- Domain-specific compiler programmed in Haskell that compiles a stencil language embedded in C++, a traditionally difficult language in which to embed a separately compiled domain-specific language.
- Implements stencils using cache-oblivious algorithm that can be parallelized using Cilk.
- Easy to express both periodic and non-periodic boundary conditions.
- There are many DSLs for expressing stencils
  - Pochoir is one of them

Pochoir
(the Language)

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End

int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);

  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);

  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) - 2.0*a(t-1,x,y) + a(t-1,x-1,y))
              + 0.125*(a(t-1,x,y+1) - 2.0*a(t-1,x,y) + a(t-1,x,y-1));
  Pochoir_Kernel_End

  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();

  heat.Run(T, kern);

  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);

  return 0;
}
```

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
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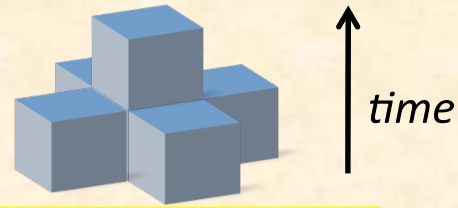
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

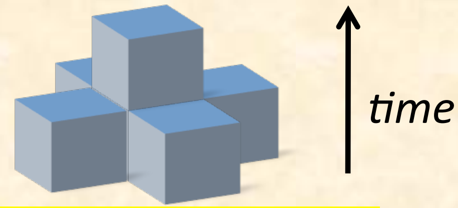


`Pochoir_Shape_`*`dim`*`D` *`name`*`[`*`count`*`]`
`=` `{`*`cells`*`};`

- *dim* is the number of spatial dimensions of the stencil.
- *name* is the name of the declared Pochoir shape.
- *count* is the length of *cells*.
- *cells* is a list of the cells in the stencil.

Declare the 2-dimensional ***Pochoir shape*** `2D_five_pt` as a list of 6 cells. Each cell specifies the relative offset of indices used in the kernel function, *e.g.*, for `a(t,x,y)`, we specify the corresponding cell `{0,0,0}`, for `a(t-1,x+1,y)`, we specify `{-1,1,0}`, and so on.

2D Heat Equation




```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
             + 0.125*(a(t-1,x+1,y) -
             + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

`Pochoir_Shape_`*dim*`D` *name*`[`*count*`]`
`= {`*cells*`};`

- *dim* is the number of spatial dimensions of the stencil.
- *name* is the name of the declared Pochoir shape.
- *count* is the length of *cells*.
- *cells* is a list of the cells in the stencil.

Declare the 2-dimensional ***Pochoir shape*** `2D_five_pt` as a list of 6 cells. Each cell specifies the relative offset of indices used in the kernel function, *e.g.*, for `a(t,x,y)`, we specify the corresponding cell `{0,0,0}`, for `a(t-1,x+1,y)`, we specify `{-1,1,0}`, and so on.

2D Heat Equation

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  return 0;
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int main(void) {
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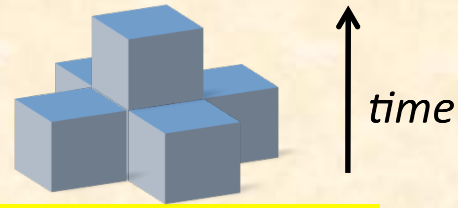
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) = a(t-1,x,y)
             + 0.125*(a(t-1,x+1,y) -
             + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```



`Pochoir_Shape_`*dim*`D` *name*`[`*count*`]`
`= {`*cells*`};`

- *dim* is the number of spatial dimensions of the stencil.
- *name* is the name of the declared Pochoir shape.
- *count* is the length of *cells*.
- *cells* is a list of the cells in the stencil.

Declare the 2-dimensional ***Pochoir shape*** `2D_five_pt` as a list of 6 cells. Each cell specifies the relative offset of indices used in the kernel function, *e.g.*, for `a(t,x,y)`, we specify the corresponding cell `{0,0,0}`, for `a(t−1,x+1,y)`, we specify `{−1,1,0}`, and so on.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

`Pochoir _`*dim*`D` *name* `(`*shape*`);`

- *dim* is the number of spatial dimensions in the stencil computation.
- *name* is the name of the Pochoir object being declared.
- *shape* is the name of a Pochoir shape.

Declare a 2-dimensional ***Pochoir object*** `heat` whose kernel function will conform to the Pochoir shape `2D_five_pt`. The Pochoir object will contain all the data and operating methods to perform the stencil computation.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

`Pochoir_Array_`*dim*`D(`*type*`)`
array`(`$size_{dim-1}$`, … ,`$size_1$`,`$size_0$`);`

- *type* is the type of the Pochoir array.
- *dim* is the number of dimensions.
- *array* is the name of the declared Pochoir array.
- $size_{dim-1}$, …, $size_1$, $size_0$, are the number of grid points along each spatial dimension, indexed from `0`.

Declare a 2-dimensional ***Pochoir array*** `a` of type `double` with spatial dimensions `X` grid points by `Y` grid points. The Pochoir array contains both underlying storage and requisite operating methods.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End

int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
                + 0.125*(a(t-1,x+1,y) - 2
                + 0.125*(a(t-1,x,y+1) - 2
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

Pochoir_Boundary_*dim*D(*name*, *array*, *time*, x_{dim-1}, …, x_1, x_0)
<definition>
Pochoir_Boundary_end

- *dim* is the number of dimensions.
- *name* is a boundary function.
- *array* is a Pochoir array.
- *time* is the time coordinate.
- x_{dim-1}, …, x_1, x_0 are the coordinates of each spatial dimension.
- *<definition>* is C++ code that returns values for *array* when it is indexed by spatial coordinates that fall outside the declared dimensions.

Declare a ***boundary function*** `zero_bdry` on the 2-dimensional Pochoir array `arr` indexed by time coordinate `t` and spatial coordinates `x` and `y`, which always returns `0`.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

array.Register_Boundary(*bdry*)

- *array* is a Pochoir array.
- *bdry* is the name of a boundary function to return a value when *array* is indexed by spatial coordinates that fall outside *array*'s declared bounds.

Register the boundary function `zero_bdry` with the Pochoir array `a`.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

name`.Register_Array(`*array*`)`

- *name* is a Pochoir object.
- *array* is a Pochoir array to register with *name*. Several Pochoir arrays can be registered with the same Pochoir object.

Register the Pochoir array `a` with the Pochoir object `heat`.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
                + 0.125*(a(t-1,x+1,y) - 2
                + 0.125*(a(t-1,x,y+1) - 2
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

Pochoir_kernel_*dim*D(*func*, *time*, x_{dim-1}, …, x_1, x_0)
  <definition>
Pochoir_kernel_end

- *dim* is the number of dimensions.
- *func* is the name of the kernel function being declared.
- *time* is the time coordinate.
- x_{dim-1}, …, x_1, x_0 are the coordinates of the spatial dimension.
- *<definition>* is C++ code that defines how each each grid point (as represented by Pochoir arrays at a given coordinate) should be updated as a function of neighboring gridpoints earlier in time.

Declare a ***kernel function*** kern with time parameter t and spatial parameters x and y.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

The Pochoir arrays can be initialized in whatever manner the programmer wishes . Time coordinates 0, 1, …, *depth* must be initialized, where *depth* is the ***shape depth***: the zero-based time dimension of the Pochoir shape (usually 1).

Initialize all points of the grid at time 0 to a random value.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) -
              + 0.125*(a(t-1,x,y+1) -
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

name.Run(*steps*, *func*)

- *name* is the name of a Pochoir object.
- *steps* is the number of time steps to run the stencil computation.
- *func* is a defined kernel function. compatible with the Pochoir shape registered with *name*.

Run a stencil computation on the Pochoir object heat for T time steps using kernel function kern. The Run method can be called multiple times.

2D Heat Equation

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
int main(void) {
  Pochoir_Shape_2D 2D_five_pt[6]
    = {{0,0,0}, {-1,1,0}, {-1,0,0}, {-1,-1,0}, {-1,0,-1}, {-1,0,1}};
  Pochoir_2D heat(2D_five_pt);
  Pochoir_Array_2D(double) a(X,Y);
  a.Register_Boundary(zero_bdry);
  heat.Register_Array(a);
  Pochoir_Kernel_2D(kern, t, x, y)
    a(t,x,y) =  a(t-1,x,y)
              + 0.125*(a(t-1,x+1,y) - …
              + 0.125*(a(t-1,x,y+1) - …
  Pochoir_Kernel_End
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      a(0,x,y) = rand();
  heat.Run(T, kern);
  for (int x = 0; x < X; ++x)
    for (int y = 0; y < Y; ++y)
      cout << a(T,x,y);
  return 0;
}
```

Elements of the Pochoir array can be read out anytime after the computation by indexing elements with time coordinate *time*+*depth*−1, where *time* is the number of steps executed and *depth* is the shape depth. The << operator is overloaded for Pochoir arrays to pretty-print their contents.

Print the elements of the Pochoir array a to standard out. The statement

```
cout << a;
```

would pretty-print the results.

Expressing Boundary Conditions

Nonperiodic zero boundary

```
Pochoir_Boundary_2D(zero_bdry, arr, t, x, y)
  return 0;
Pochoir_Boundary_End
```

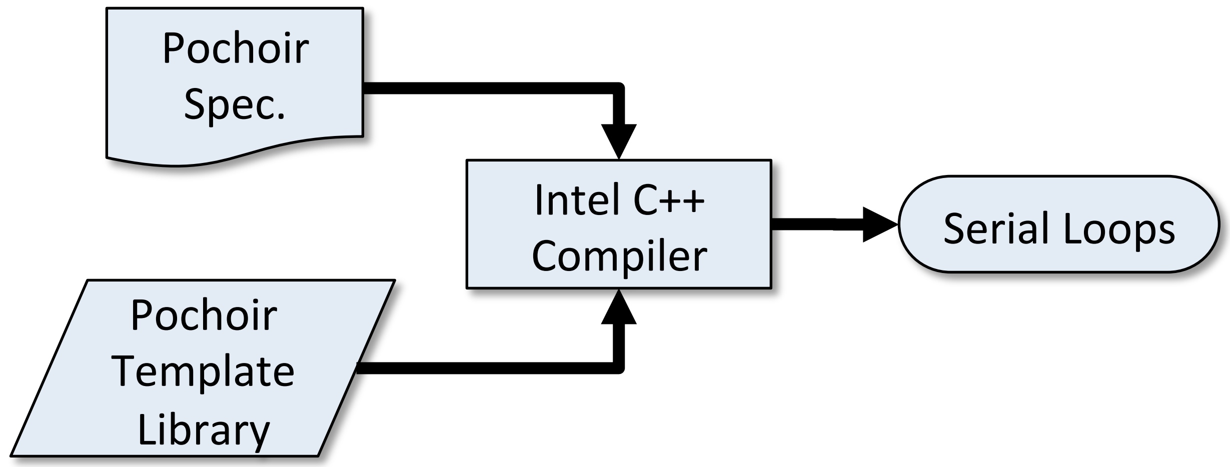
Periodic (toroidal) boundary

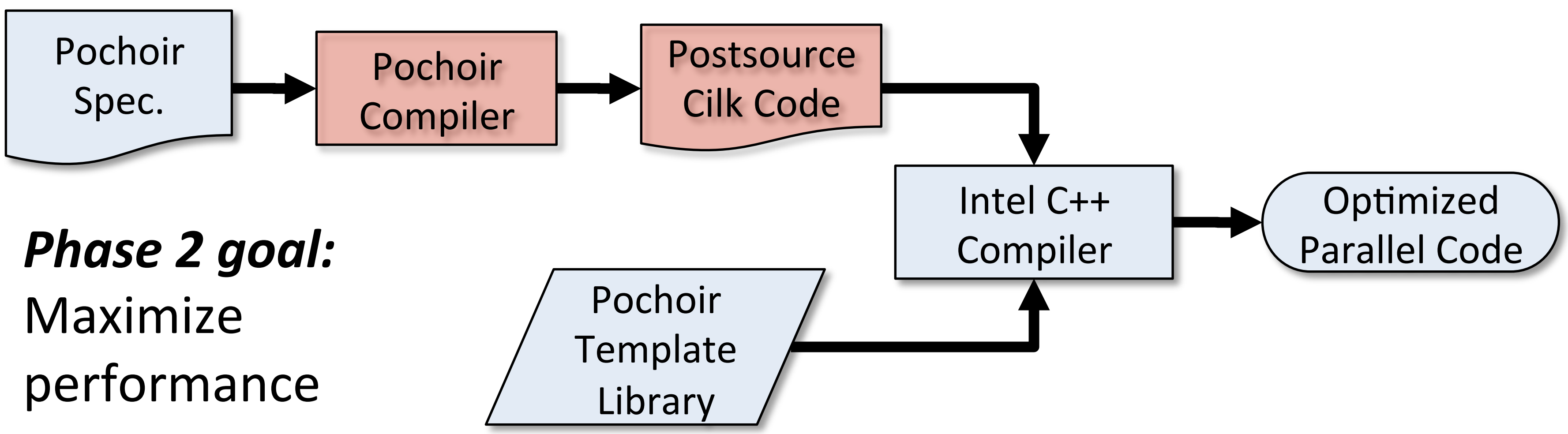
```
#define mod(r,m) (((r) % (m)) + ((r)<0)?(m):0)
Pochoir_Boundary_2D(periodic, arr, t, x, y)
  return arr.get( t,
                  mod(x, arr.size(1)),
                  mod(y, arr.size(0)) );
Pochoir_Boundary_End
```

Pochoir
(the Compiler)

Two-Phase Compilation Strategy

Phase 1 goal:
Check functional correctness

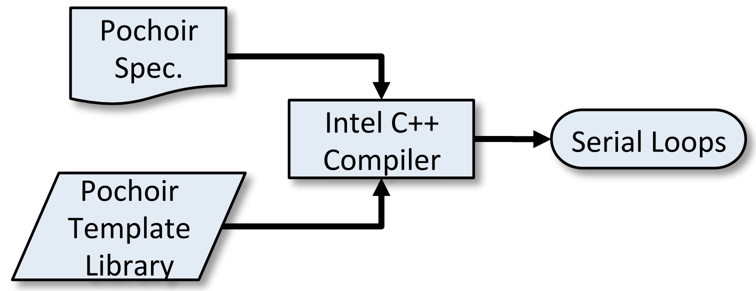




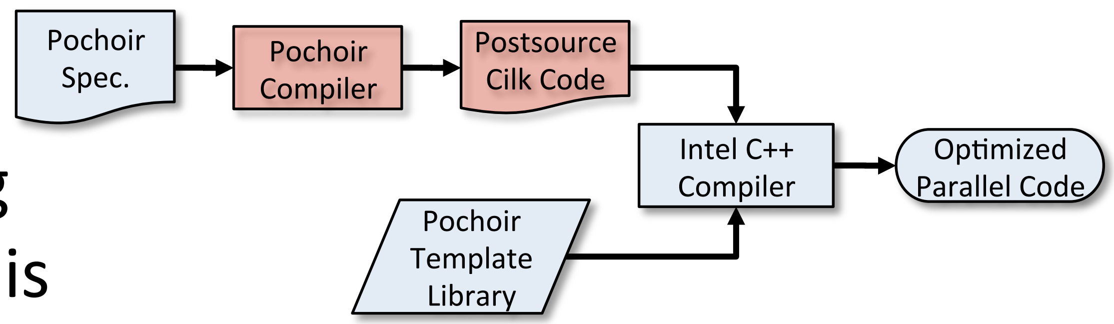
Phase 2 goal:
Maximize performance

Pochoir Guarantee

If a stencil program compiles and runs with the Pochoir template library during Phase 1,



then no errors will occur during Phase 2 when it is compiled with the Pochoir compiler or during the subsequent running of the optimized binary.



Why is this important?

Impact of the Pochoir Guarantee

- The Pochoir compiler can parse as much of the programmer's C++ code as it is able without worrying about parsing it all.

- If the Pochoir compiler can "understand" the code, which it can in the common case, it can perform strong optimizations.

- If the Pochoir compiler cannot "understand" the code, it can treat the code as correct uninterpreted C++ text and rely on base C++ compiler

Pochoir
(the Implementation)

Optimizations

- Two code clones
- Unifying the handling of periodic and nonperiodic boundary conditions
- Automatic selection of optimizing strategy
- Coarsening of base cases

Two Code Clones

- The ***slow clone*** handles regions that contain boundaries and checks for out-of-range grid points.
- The ***fast clone*** handles the larger interior regions which require no range checking.

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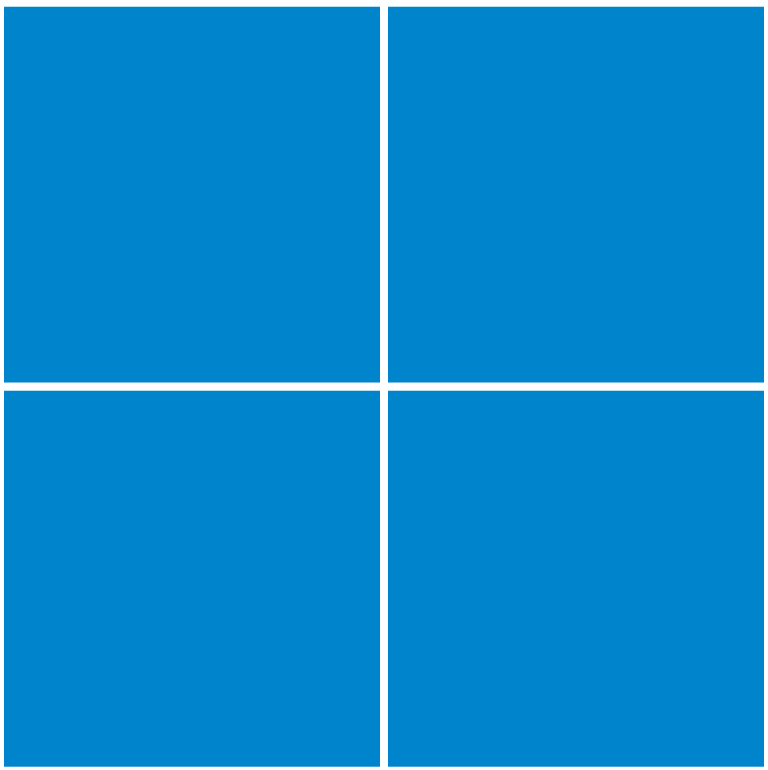

During the recursive algorithm, the fast clone is used whenever possible.

Two Code Clones

- The ***slow clone*** handles regions that contain boundaries and checks for out-of-range grid points.
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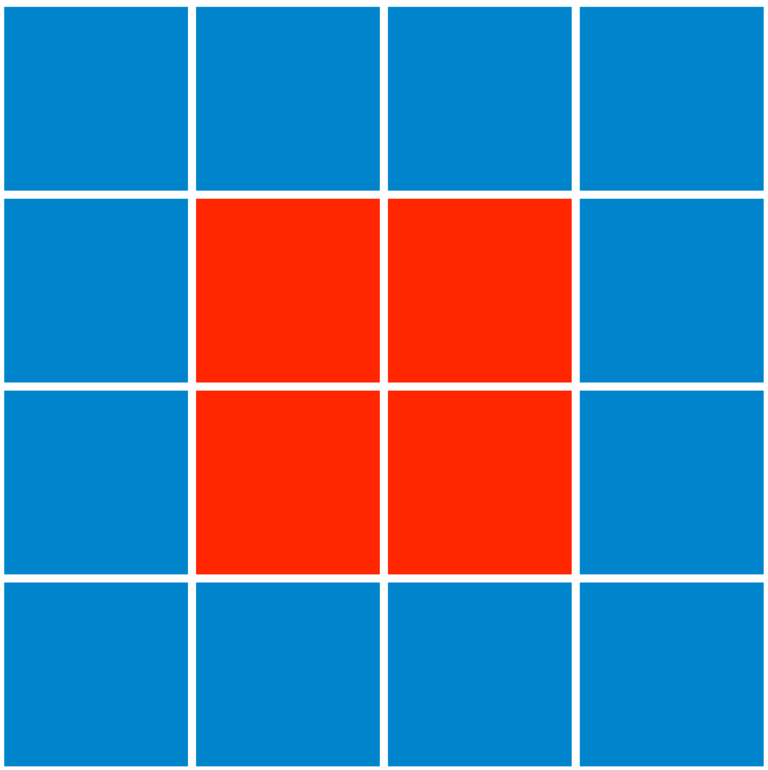

During the recursive algorithm, the fast clone is used whenever possible. Once the fast clone is used for a region, the fast clone is always used for its subregions.

Two Code Clones

- The ***slow clone*** handles regions that contain boundaries and checks for out-of-range grid points.
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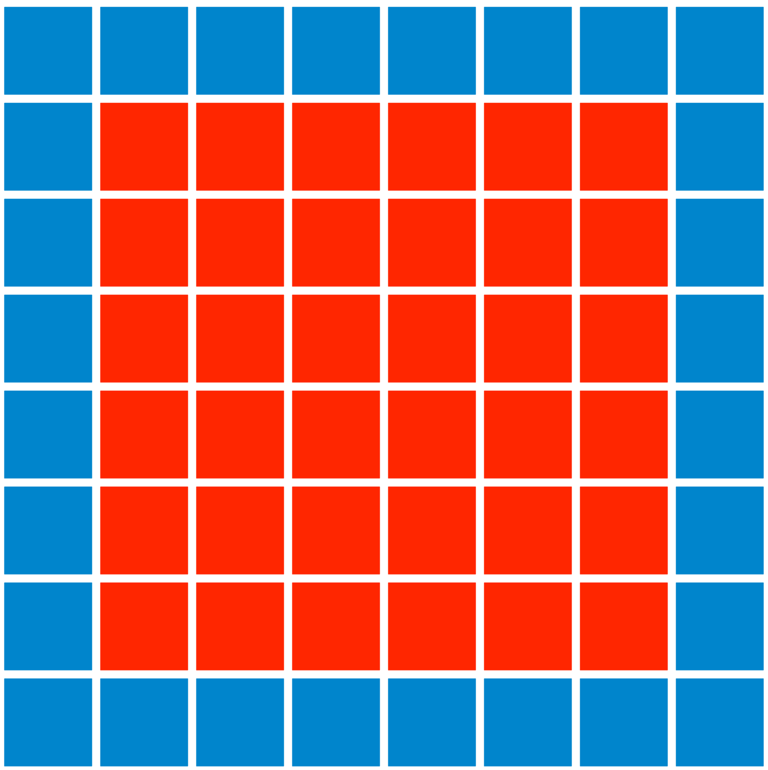

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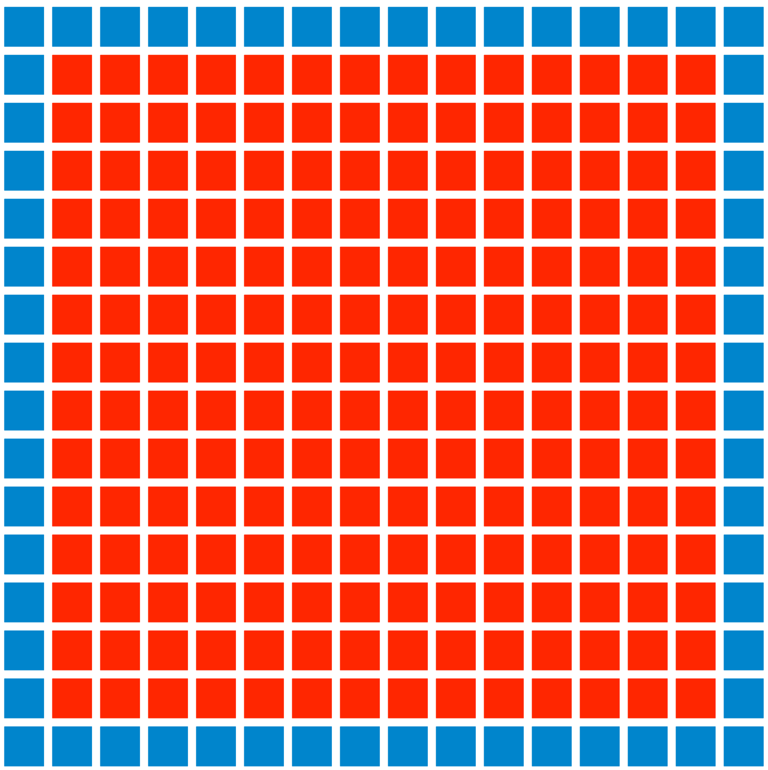

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Lessons Learned

- Design specific constructs for domain
- Constructs need to easily map to underlying target language
- Exposing high-level structure allows domain-specific optimizations