The Pochoir Stencil Compiler

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The Pochoir Stencil Compiler

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Chi-Keung Luk  Charles E. Leiserson

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ABSTRACT
A stencil computation repeatedly updates each point of a d-dimensional grid as a function of itself and its near neighbors. Parallel cache-efficient stencil algorithms based on “trapezoidal decompositions” are known, but most programmers find them difficult to write. The Pochoir stencil compiler allows a programmer to write a simple specification of a stencil in a domain-specific stencil language embedded in C++ which the Pochoir compiler then translates into high-performing Cilk code that employs an efficient parallel cache-oblivious algorithm. Pochoir supports general d-dimensional stencils and handles both periodic and aperiodic boundary conditions in one unified algorithm. The Pochoir system provides a C++ template library that allows the user’s stencil specification to be executed directly in C++ without the Pochoir compiler (albeit more slowly), which simplifies user debugging and greatly simplifies the implementation of the Pochoir compiler itself. A host of stencil benchmarks run on a modern multicore machine demonstrates that Pochoir outperforms standard parallel-loop implementations, typically running 2–10 times faster. The algorithm behind Pochoir improves on prior cache-efficient algorithms by greatly simplifying the implementation of the Pochoir compiler itself.

Categories and Subject Descriptors
D.1.3 [Programming Techniques]: Concurrent Programming—Parallel programming; D.3.2 [Programming Languages]: Language Classifications—Specialized application languages; G.4 [Mathematical Software]: Algorithm design and analysis.

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General Terms
Algorithms, Languages, Performance.

Keywords

1. INTRODUCTION
Pochoir (pronounced “PO-shwar”) is a compiler and runtime system for implementing stencil computations on multicore processors. A stencil defines the value of a grid point in a d-dimensional spatial grid at time \( t \) as a function of neighboring grid points at recent times before \( t \). A stencil computation [2, 9, 11, 12, 16, 17, 26–28, 33, 34, 36, 40, 41] computes the stencil for each grid point over many time steps.

Stencil computations are conceptually simple to implement using nested loops, but looping implementations suffer from poor cache performance. Cache-oblivious [15, 38] divide-and-conquer stencil codes [16, 17] are much more efficient, but they are difficult to write, and when parallelism is factored into the mix, most application programmers do not have the programming skills or patience to produce efficient multithreaded codes.

As an example, consider how the 2D heat equation [13]

\[
\frac{\partial u_t(x,y)}{\partial t} = \alpha \left( \frac{\partial^2 u_t(x,y)}{\partial x^2} + \frac{\partial^2 u_t(x,y)}{\partial y^2} \right)
\]

on an \( X \times Y \) grid, where \( u_t(x,y) \) is the heat at a point \((x,y)\) at time \( t \) and \( \alpha \) is the thermal diffusivity, might be solved using a stencil computation. By discretizing space and time, this partial differential equation can be solved approximately by using the following Jacobi-style update equation:

\[
u_{t+1}(x,y) \quad = \quad u_t(x,y)
+ \frac{\alpha \Delta t}{\Delta x^2} \left( u_t(x-1,y) + u_t(x+1,y) - 2u_t(x,y) \right)
+ \frac{\alpha \Delta t}{\Delta y^2} \left( u_t(x,y-1) + u_t(x,y+1) - 2u_t(x,y) \right).
\]

One simple parallel program to implement a stencil computation based on this update equation is with a triply nested loop, as shown in Figure 1. The code is invoked as \texttt{LOOPS(x;0,T;0,X;0,Y)} to perform the stencil computation over \( T \) time steps. Although the loop indexing the time dimension is serial, the loops indexing the spatial dimensions can be parallelized, although as a practical matter, only the outer loop needs to be parallelized. There is generally no need to store the entire space-time grid, and so the code uses two
copies of the spatial grid, swapping their roles on alternate time steps. This code assumes that the boundary conditions are periodic, meaning that the spatial grid wraps around to form a torus, and hence the index calculations for \( x \) and \( y \) are performed modulo \( X \) and \( Y \), respectively.

This loop nest is simple and fairly easy to understand, but its performance may suffer from poor cache locality. Let \( M \) be the number of grid points that fit in cache, and let \( B \) be the number of grid points that fit on a cache line. If the space grid does not fit in cache, and hence the index calculations for \( x \) and \( y \) are performed modulo \( X \) and \( Y \), respectively.

Figure 2 shows the pseudocode for a more efficient cache-oblivious algorithm called \( \text{TRAP} \), which is the basis of the algorithm used by the Pochoir compiler. We shall explain this algorithm in Section 3. It achieves \( \Theta(TXY/B\sqrt{M}) \) cache misses, assuming that \( X \approx Y = T = \Omega(X) \). \( \text{TRAP} \) easily outperforms \( \text{LOOPS} \) on large data sets. For example, we ran both algorithms on a 5000 x 5000 spatial grid iterated for 5000 time steps using the Intel C++ version 12.0.0 compiler with Intel Cilk Plus [23] on a 12-core Intel Core i7 (Nehalem) machine with a private 32-KB L1-data-cache, a private 256-KB L2-cache, and a shared 12-MB L3-cache. The code based on \( \text{LOOPS} \) ran in 248 seconds, whereas the Pochoir-generated code based on \( \text{TRAP} \) required about 24 seconds, more than a factor of 10 performance advantage.

Figure 3 shows Pochoir’s performance on a wider range of benchmarks, including heat equation (Heat) [13] on a 2D grid, a 2D torus, and a 4D grid; Conway’s game of Life (Life) [18]; 3D finite-difference wave equation (Wave) [32]; lattice Boltzmann method (LBM) [30]; RNA secondary structure prediction (RNA) [1, 6]; pairwise sequence alignment (PSA) [19]; longest common subsequence (LCS) [7]; and American put stock option pricing (APOP) [24]. Pochoir achieves a substantial performance improvement over a straightforward loop parallelization for typical stencil applications, such as Heat and Life. Even LBM, which is a complex stencil having many states, achieves good speedup. When Pochoir does not achieve as much speedup over the loop code, it is often due to the spatial grid being too small to yield good parallelism, the innermost loop containing many branch conditionals, or the benchmark containing a high ratio of memory accesses to floating-point operations. For example, RNA’s small grid size of 300\(^2\) yields a parallelism of just over 5 for both Pochoir and parallel loops, and its innermost loop contains many branch conditionals. PSA operates over a diamond-shaped domain, and so the application employs many conditional branches in the kernel in order to distinguish interior points from exterior points. These overheads can sometimes significantly mitigate a cache-efficient algorithm’s advantage in incurring fewer cache misses.
only a single time step, whereas the Pochoir code runs for 200 time steps. (It does not make sense to run Pochoir for only 1 time step, since its efficiency is in large measure due to the temporal locality of cache use.) Likewise, the Pochoir figures may exhibit a disadvantage compared with the Berkeley ones, because Pochoir had to cope with load imbalances due to the scheduling of 8 threads on 12 cores. Notwithstanding these issues, as can be seen from the figure, Pochoir’s performance is generally comparable to that of the Berkeley autotuner on these two benchmarks.

The Pochoir-generated TRAP code is a cache-oblivious [15,38] divide-and-conquer algorithm based on the notion of trapezoidal decompositions introduced by Frigo and Strumpen [16,17]. We improve on their code by using hyperspace cuts, which produce an asymptotic improvement in parallelism while attaining essentially the same cache efficiency. As can be seen from Figure 2, however, this divide-and-conquer parallel code is far more complex than LOOPS, involving recursion over irregular geometric regions. Moreover, TRAP presents many opportunities for optimization, including coarsening the base case of the recursion and handling boundary conditions. We contend that one cannot expect average application programmers to be able to write such complex high-performing code for each stencil computation they wish to perform.

The Pochoir stencil compiler allows programmers to write simple functional specification for arbitrary d-dimensional stencils, and then it automatically produces a highly optimized, cache-efficient, parallel implementation. The Pochoir language can be viewed as a domain-specific language [10,21,31] embedded in the base language C++ with the Cilk multithreading extensions [23].

As shown in Figure 4, the Pochoir system operates in two phases, only the second of which involves the Pochoir compiler itself. For the first phase, the programmer compiles the source program with the ordinary Intel C++ compiler using the Pochoir template library, which implements Pochoir’s linguistic constructs using unoptimized but functionally correct algorithms. This phase ensures that the source program is Pochoir-compliant. For the second phase, the programmer runs the source through the Pochoir compiler, which acts as a preprocessor to the Intel C++ compiler, performing a source-to-source translation into a postsource C++ program that employs the Cilk extensions. The postsource is then compiled with the Intel compiler to produce the optimized binary executable.

The Pochoir compiler makes the following promise:

**The Pochoir Guarantee:** If the stencil program compiles and runs with the Pochoir template library during Phase 1, no errors will occur during Phase 2 when it

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Dims</th>
<th>Grid size</th>
<th>Time steps</th>
<th>1 core</th>
<th>Pochoir 12 cores speedup</th>
<th>Serial loops time ratio</th>
<th>12-core loops time ratio</th>
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<tr>
<td>Heat 2</td>
<td>16,000²</td>
<td>500</td>
<td>277s 24s 11.5</td>
<td>612s 25.5</td>
<td>149s 6.2</td>
<td></td>
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<tr>
<td>Heat 2p</td>
<td>16,000²</td>
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<td>281s 24s 11.7</td>
<td>1,647s 68.6</td>
<td>248s 10.3</td>
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<td></td>
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<tr>
<td>Heat 4</td>
<td>150³</td>
<td>100</td>
<td>154s 54s 2.9</td>
<td>433s 8.0</td>
<td>104s 1.9</td>
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<tr>
<td>Life 2</td>
<td>16,000²</td>
<td>500</td>
<td>345s 28s 12.3</td>
<td>2,419s 86.4</td>
<td>332s 11.9</td>
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<tr>
<td>Wave 3</td>
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<td>500</td>
<td>3,082s 447s 6.9</td>
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<td>1,071s 2.4</td>
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<td>LBM 3</td>
<td>100³ × 130</td>
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<td>304s 4.5</td>
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<tr>
<td>RNA 2</td>
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<td>900</td>
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<td>26s 1.3</td>
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<td>200,000</td>
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<td>APOP 1</td>
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<td>10,000</td>
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<td>515s 128.8</td>
<td>48s 12.0</td>
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**Figure 3:** Pochoir performance on an Intel Core i7 (Nehalem) machine. The stencils are nonperiodic unless the Dims column contains a “p.” The header Serial loops means a serial for loop implementation running on one core, whereas 12-core loops means a parallel cilk_for loop implementation running on 12 cores. The header ratio indicates how much slower the looping implementation is than the 12-core Pochoir implementation. For nonperiodic stencils, the looping implementations employ ghost cells [8] to avoid boundary processing.

<table>
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<td>Xeon X5650</td>
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<tr>
<td>cores/socket</td>
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<td>256KB</td>
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<tr>
<td>Peak computation</td>
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<td>120 GBFLOPS</td>
</tr>
<tr>
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<td>Cilk Plus</td>
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<tr>
<td>Linux kernel</td>
<td>icc 10.0.0</td>
<td>icc 12.0.0</td>
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<tr>
<td>Threading model</td>
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<td>2.6.32</td>
</tr>
<tr>
<td>3D 7-point</td>
<td>2.0 GFLOPS/s</td>
<td>2.49 GFLOPS/s</td>
</tr>
<tr>
<td>8 cores</td>
<td>15.8 GBFLOPS</td>
<td>19.92 GBFLOPS</td>
</tr>
<tr>
<td>3D 27-point</td>
<td>0.95 GFLOPS/s</td>
<td>0.88 GFLOPS/s</td>
</tr>
<tr>
<td>8 cores</td>
<td>28.5 GBFLOPS</td>
<td>26.4 GBFLOPS</td>
</tr>
</tbody>
</table>

**Figure 5:** A comparison of Pochoir to the reported results from [8]. The 7-point stencil requires 8 floating-point operations per grid point, whereas the 27-point stencil requires 30 floating-point operations per grid point.

...is compiled with the Pochoir compiler or during the subsequent running of the optimized binary.

Pochoir’s novel two-phase compilation strategy allowed us to build significant domain-specific optimizations into the Pochoir compiler without taking on the massive job of parsing and type-checking the full C++ language. Knowing that the source program compiles error-free with the Pochoir template library during Phase 1 allows the Pochoir compiler in Phase 2 to treat portions of the source as uninterpreted text, confident that the Intel compiler will compile it correctly in the optimized postsource. Moreover, the Pochoir template library allows the programmer to debug his or her code using a comfortable native C++ tool chain without the complications of the Pochoir compiler.

Figure 6 shows the Pochoir source code for the periodic 2D heat equation. We leave the specification of the Pochoir language to Section 2, but outline the salient features of the language using this code as an example.

Line 7 declares the Pochoir shape of the stencil, and line 8 creates the 2-dimensional Pochoir object heat having that shape. The Pochoir object will contain all the state necessary to perform the computation. Each triple in the array 2D_five_pt corresponds to a relative offset from the space-time grid point \((x,y)\) that the stencil kernel (declared in lines 12–14) will access. The compiler cannot infer the stencil shape from the kernel, because the kernel can be arbitrary code, and accesses to the grid points can be hidden in subroutines. The Pochoir template library complains during Phase 1, however, if an access to a grid point during the kernel computation falls outside the region specified by the shape declaration.
Line 18 executes the stencil object `heat` for `T` time steps using kernel function `heat_fn`. Lines 19–21 prints the result of the computation by reading the elements `u(t, x, y)` of the Pochoir array. In fact, Pochoir overloads the `"<<"` operator so that the Pochoir array can be pretty-printed by simply writing `"cout << u;"`.

The remainder of this paper is organized as follows. Section 2 provides a full specification of the Pochoir embedded language. Section 3 describes the cache-oblivious parallel algorithm used by the compiled code and analyzes its theoretical performance. Section 4 describes four important optimizations employed by the Pochoir compiler. Section 5 describes related work, and Section 6 offers some concluding remarks.

## 2. THE POCHOIR SPECIFICATION LANGUAGE

This section describes the formal syntax and semantics of the Pochoir language, which was designed with a view to offer as much expressiveness as possible while avoiding the Pochoir Guarantee. Since we wanted to allow third-party developers to implement their own stencil compilers that could use the Pochoir specification language, we avoided the extent possible making the language too specific to the Pochoir compiler, the Intel C++ compiler, and the multicore machines we used for benchmarking.

The static information about a Pochoir stencil computation, such as the computing kernel, the boundary conditions, and the stencil shape, is stored in a Pochoir object, which is declared as follows:

- **Pochoir_dimD name (shape):**

  This statement declares `name` as a Pochoir object with `dim` spatial dimensions and computing shape `shape`, where `dim` is a small positive integer and `shape` is an array of arrays which describes the shape of the stencil as elaborated below.

  We now itemize the remaining Pochoir constructs and explain the semantics of each.

- **Pochoir_Shape_dimD name [[]] = [cells]**

  This statement declares `name` as a Pochoir shape that can hold shape information for `dim` spatial dimensions. The Pochoir shape is equivalent to an array of arrays, each of which contains `dim + 1` integer numbers. These numbers represent the offset of each memory footprint in the stencil kernel relative to the space-time grid point `(t,x,y,···)`. For example, suppose that the computing kernel employs the following update equation:

  \[
  u_t(x,y) = u_{t-1}(x,y) + \frac{\alpha}{\Delta x^2}(u_{t-1}(x-1,y) + u_{t-1}(x+1,y) - 2u_{t-1}(x,y))
  + \frac{\alpha}{\Delta y^2}(u_{t-1}(x,y-1) + u_{t-1}(x,y+1) - 2u_{t-1}(x,y)).
  \]

  The shape of this stencil is \{\{0,0,0\}, \{-1,1,0\}, \{-1,0,0\},
  \{-1,−1,0\}, \{-1,0,1\}, \{-1,0,−1\}\}.
The first cell in the shape is the home cell, whose spatial coordinates must all be 0. During the computation, this cell corresponds to the grid point being updated. The remaining cells must have time offsets that are smaller than the time coordinate of the home cell, and the corresponding grid points during the computation are read-only.

The depth of a shape is the time coordinate of the home cell minus the minimum time coordinate of any cell in the shape. The depth corresponds to the number of time steps on which a grid point depends. For our example stencil, the depth of the shape is 1, since a point at time \( t \) depends on points at time \( t - 1 \). If a stencil shape has depth \( k \), the programmer must initialize all Pochoir arrays for time steps \( 0, 1, \ldots, k - 1 \) before running the computation.

- **Pochoir_Array_dimD** (type, depth) name \((size_{dim-1}, \ldots, size_1, size_0)\)

This statement declares name as a Pochoir array of type with \( dim \) spatial dimensions and a temporal dimension. The size of the \( i \)th spatial dimension, where \( i \in \{0, 1, \ldots, dim\} \), is given by \( size_i \). The temporal dimension has size \( k + 1 \), where \( k \) is the depth of the Pochoir shape, and are reused modulo \( k + 1 \) as the computation proceeds. The user may not obtain an alias to the Pochoir array or its elements.

- **Pochoir_Boundary_dimD** (name, array, idx1, idx2, \( \ldots, idx_{dim-1} \), \( idx_1, idx_0 \))

This construct defines a boundary function called name that will be invoked to supply a value when the stencil computation accesses a point outside the domain of the Pochoir array. The Pochoir array has \( dim \) spatial dimensions, and \( (idx_{dim-1}, \ldots, idx_1, idx_0) \) are the spatial coordinates of the given point outside of the domain of array. The coordinate in the time dimension is given by \( idx_0 \). The function body \((\text{definition})\) is C++ code that defines the values of array on its boundary. A current restriction is that this construct must be declared outside of any function, that is, the boundary function is declared global.

- **Pochoir_Kernel_dimD** (name, array, idx1, idx2, \( \ldots, idx_{dim-1} \), \( idx_1, idx_0 \))

This construct defines a kernel function named name for updating a stencil on a spatial grid with \( dim \) spatial dimensions. The spatial coordinates of the point to update are \( (idx_{dim-1}, \ldots, idx_1, idx_0) \), and \( idx_1 \) is the coordinate in time dimension. The function body \((\text{definition})\) may contain arbitrary C++ code to compute the stencil. Unlike boundary functions, this construct can be defined in any context.

- **name.Register_Array** (array)

A call to this member function of a Pochoir object name informs name that the Pochoir array array will participate in its stencil computation.

- **name.Register_Boundary** (bdry)

A call to this member function of a Pochoir array name associates the declared boundary function bdry with name. The boundary function is invoked to supply a value whenever an off-domain memory access occurs. Each Pochoir array is associated with exactly one boundary function at any given time, but the programmer can change boundary functions by registering a new one.

- **name.Run** (\( T, \text{kern} \))

This function call runs the stencil computation on the Pochoir object name for \( T \) time steps using computing kernel function kern. After running the computation for \( T \) steps, the results of the computation can be accessed by indexing its Pochoir arrays at time \( T + k - 1 \), where \( k \) is the depth of the stencil shape. The programmer may resume the running of the stencil after examining the result of the computation by calling name.Run\((T, \text{kern})\), where \( T' \) is the number of additional steps to execute. The result of the computation is then in the computation’s Pochoir arrays indexed by time \( T + T' + k - 1 \).

**Rationale**

The Pochoir language is a product of many design decisions, some of which were influenced by the current capabilities of the Intel 12.0.0 C++ compiler. We now discuss some of the more important design decisions.

Although we chose to pass a kernel function to the Run method of a Pochoir object, we would have preferred to simply store the kernel function with the Pochoir object. The kernel function is a C++ lambda function [5], however, whose type is not available to us. Thus, although we can pass the lambda function as a template type, we cannot store it unless we create a \texttt{std::function} to capture its type. Since the Intel compiler does not yet support \texttt{std::function}, this avenue was lost to us. There is only one kernel function per Pochoir object, however, and so we decided as a second-best alternative that it would be most convenient for users if they could declare a kernel function in any context and we just pass it as an argument to the Run member function.

The lack of support for function objects also had an impact on the declaration of boundary functions. We wanted to store each boundary function with a Pochoir array so that whenever an access to the array falls outside the computing domain, we can call the boundary function to supply a value. The only way to create a function that can be stored is to use an ordinary function, which must be declared in a global scope. We hope to improve Pochoir’s linguistic design when function objects are fully supported by the compiler.

We chose to specify the kernel function imperatively rather than as a pure function or as an expression that returns a value for the grid point being updated. This approach allows a user to write multiple statements in a kernel function and provides flexibility on how to specify a stencil formula. For example, the user can choose to specify a stencil formula as \( a(t, i, j) = \ldots \text{or} \ a(t+1, i, j) = \ldots \) whichever is more convenient.

We chose to make the user copy data in and out of Pochoir internal data structures, rather than operate directly on the user’s arrays. Since the user is typically running the stencil computation for many time steps, we decided that the copy-in/copy-out approach would not cause much overhead. Moreover, the layout of data is now under the control of the compiler, allowing it to optimize the storage for cache efficiency.

### 3. POCHOIR’S CACHE-OBLIVIOUS PARALLEL ALGORITHM

This section describes the parallel algorithm at the core of Pochoir’s efficiency. TRAP is a cache-oblivious algorithm based on “trapezoidal decompositions” [16, 17], but which employs a novel “hyperspace-cut” strategy to improve parallelism without sacrificing cache-efficiency. On a \( d \)-dimensional spatial grid with all “normalized” spatial dimensions equal to \( w \) and the time dimension a \( \Theta(w^{d-\log(d+2)+1}/d^2) \) parallelism, whereas Frigo and Strumpe...
original parallel trapezoidal decomposition algorithm [17] achieves \(\Theta(w^{d-\log^2(2^d+1)/2^d}) = O(w)\) parallelism. Both algorithms exhibit the same asymptotic cache complexity of \(\Theta(M^{d/3}/M^{1/12}B)\) proved by Frigo and Strumpen, where \(h\) is the height of the time dimension, \(M\) is the cache size, and \(B\) is the cache-block size.

TRAP uses a cache-oblivious [15] divide-and-conquer strategy based on a recursive trapezoidal decomposition of the space-time grid, which was introduced by Frigo and Strumpen [16]. They originally used the technique for serial stencil computations, but later extended it to parallel stencil computations [17]. Whereas Frigo and Strumpen’s parallel algorithm cuts the spatial dimensions of a hypertrapezoid, or “zoid,” one at a time with “parallel space cuts.” TRAP performs a *hyperspace cut* where it applies parallel space cuts simultaneously to as many dimensions as possible, yielding asymptotically more parallelism when the number of spatial dimensions is 2 or greater. As we will argue later in this section, TRAP achieves this improvement in parallelism while attaining the same cache complexity as Frigo and Strumpen’s original parallel algorithm.

TRAP operates as follows. Line 5 of Figure 2 determines whether the \(x\)-dimension of the zoid can be cut with a parallel space cut, and if so, line 6 trisects the zoid, as we shall describe later in this section and in Figure 7, but it does not immediately spawn recursive tasks to process the subzoids, as Frigo and Strumpen’s algorithm would. Instead, the code attempts to make a “hyperspace cut” by proceeding to the \(y\)-dimension, and if there were more dimensions, to those, cutting as many dimensions as possible before spawning recursive tasks to handle the subzoids. The counter \(k\) keeps track of how many spatial dimensions are cut. If \(k > 0\) spatial dimensions are trisected, as tested for in line 11, then line 12 assigns each subzoid to one of \(k + 1\) dependency levels such that the subzoids assigned to the same level are independent and can be processed in parallel, as we describe later in this section and in Figure 8. Lines 13–15 recursively walk all subzoids level by level in parallel. Lines 17–19 perform a time cut if no space cut can be performed. Lines 20–28 perform the base-case computation if the zoid is sufficiently small that no space or time cut is productive.

We first introduce some notations and definitions, many of which have been borrowed or adapted from [16, 17]. A \((d + 1)\)-dimensional space-time trapezoidal decomposition (or \((d + 1)\)-zoid), \(Z = (\tau, \delta, x_0, x_1, \ldots, x_d, a, b, x^{\tau}_1, x^{\tau}_2, \ldots, x^{\tau}_d, x_{\delta}^{\tau})\), where all variables are integers, is the set of integer grid points \((t, x_0, x_1, \ldots, x_d)\) such that \(ta \leq \tau \leq \delta t\) and \(x_i + dx_i^\tau(t - ta) \leq \tau \leq \delta x_i + dx_i^\tau(t - ta)\) for all \(i \in \{0, 1, \ldots, d - 1\}\). The height of \(Z\) is \(\delta = \tau - \tau\). Define the *projection zoid* \(Z_i\) of \(Z\) along spatial dimension \(i\) to be the \(2D\) trapezoid that results from projecting the zoid \(Z\) onto the dimensions \(x_i\) and \(t\). The projection zoid \(Z_i\) has two bases (sides parallel to the \(x_i\) axis) of lengths \(\Delta x_i = x_{\delta} - x_\tau\) and \(V_{x_i} = (x_{\delta} + dx_{\delta}) - (x_\tau + dx_\tau)\). We define the *width* \(w_i\) of \(Z_i\) to be the length of the longer of the two bases (parallel sides) of \(Z_i\), that is \(w_i = \max(\Delta x_i, V_{x_i})\). The value \(w_i\) is also called the *width of \(Z\) along spatial dimension \(i\)*. We say that \(Z_i\) is *upright* if \(w_i = \Delta x_i\) — the longer base corresponds to time \(ta\) — and *inverted* otherwise. A zoid \(Z\) is *well-defined* if its height is positive, its widths along all spatial dimensions are positive, and the lengths of its bases along all spatial dimensions are nonnegative. A projection zoid \(Z_i\) is *minimal* if \(Z_i\) is upright and \(V_{x_i} = 0\), or \(Z_i\) is inverted and \(\Delta x_i = 0\). A zoid \(Z\) is *minimal* if all its \(Z_i\)’s are minimal.

Given the shape \(S\) of a \(d\)-dimensional stencil (as described in

---

\(1\)Frigo and Strumpen [16, 17] define width as the average of the two bases.

\(2\)Actually, the reciprocal of slope, but we follow Frigo and Strumpen’s terminology.

---

**Figure 7**: Cutting projection trapezoids. The spatial dimension increases to the right, and the time runs upward. (a) Trisecting an upright trapezoid using a parallel space cut produces two black trapezoids that can be processed in parallel and a gray trapezoid that must be processed after the black ones. (b) Trisecting an inverted trapezoid using a parallel space cut produces two black trapezoids that can be processed in parallel and a gray trapezoid that must be processed before the black ones. (c) A time cut produces a lower and an upper trapezoid where the lower trapezoid must be processed before the upper.

**Parallel space cuts**

Our trapezoidal decomposition differs from that of Strumpen and Frigo in the way we do parallel space cuts. A *parallel space cut* can be applied along a given spatial dimension \(i\) of a well-defined zoid \(Z\) provided that the projection zoid \(Z_i\) can be trisected into 3 well-defined subtrapezoids, as shown in Figures 7(a) and 7(b). The triangle-shaped gray subtrapezoid that lies in the middle is a minimal trapezoid. The larger base of \(Z_i\) is split in half with each half forming the larger base of a black subtrapezoid. These three sub-trapezoids of \(Z_i\) correspond to three subzoids of \(Z\). Since the two black subzoids have no interdependencies, they can be processed in parallel. As shown in Figure 7(a), for an upright projection trapezoid, the subzoids corresponding to the black trapezoids are processed first, after which the subzoid corresponding to the gray subtrapezoid can be processed. For an inverted projection trape-
both of whose projection trapezoids are inverted, generated by a

k

applied, as shown in Figures 7(a) and 7(b). If the number

k

is

computed for all resulting subzoids in line 12, and then lines 13–15

Pochoir’s cache-oblivious parallel algorithm

Given a well-defined zoid \( Z \), the algorithm TRAP from Figure 2
works by recursively decomposing \( Z \) into smaller well-defined
zoids as follows.

**Hyperspace cut.** Lines 4–10 in Figure 2 apply a hyperspace

cut involving all dimensions on which a parallel space cut can be
applied, as shown in Figures 7(a) and 7(b). If the number \( k \) of

dimensions of \( Z \) on which a space cut can be applied is at least

1, as tested for in line 11 of Figure 2, then dependency levels are
computed for all resulting subzoids in line 12, and then lines 13–15
recursively process them in order according to dependency level as
described in the proof of Lemma 1.

**Time cut.** If a hyperspace cut is not applicable and \( Z \) has height
greater than 1, as tested for in line 16, then lines 17–19 cut \( Z \)
in the middle of its time dimension and recursively process the lower
subzoid followed by the upper subzoid, as shown in Figure 7(c).

**Base case.** If neither a hyperspace cut nor a time cut can be
applied, lines 20–28 processes \( Z \) directly by invoking the stencil-
specific kernel function. In practice, the base case is *coarsened*
(see Section 4) by choosing a suitable threshold larger than 1 for \( \Delta t \)
in line 16, which cuts down on overhead due to the recursion.

**Analysis**

We can analyze the parallelism using a work/span analysis [7, Ch. 27]
. The work \( T_1 \) of a computation is its serial running time, and the
span \( T_\text{span} \) is the longest path of dependencies, or equivalently,
the running time on an infinite number of processors assuming
no overheads for scheduling. The **parallelism** of a computation is
the ratio \( T_1 / T_\text{span} \) of work to span.

The next lemma provides a tight bound on the span of TRAP
algorithm on a minimal zoid.

**Lemma 2.** Consider a minimal \((d + 1)\)-zoid \( Z \) with height \( h \)
and normalized widths \( \bar{w}_i = h \) for \( i \in \{0, 1, \ldots, d - 1\} \). Then the
span of TRAP when processing \( Z \) is \( \Theta(d^h h^\Theta(d + 2)) \).

**Proof.** For simplicity we assume that a call to the kernel function
costs \( O(1) \), as in [17]. As TRAP processes \( Z \), some of the
subzoids generated recursively have normalized widths equal to
their heights and some have twice that amount. Let us denote by

\( T_\text{span}(h, k, d - k) \) the span of TRAP processing a \((d + 1)\)-zoid
with height \( h \) where \( k \geq 0 \) of the \( d \) spatial dimensions have normalized
width \( 2h \) and \( d - k \) spatial dimensions have normalized width \( h \).

Using Lemma 1, the span of TRAP processing a zoid \( Z \) when it
undergoes a hyperspace cut can be described by the recurrence

\[
T_\text{span}(h, k, d - k) = (k + 1)T_\text{span}(h, 0, d) + \Theta \left( \sum_{i=0}^{k} \lg(3^i) \right) \\
= (k + 1)T_\text{span}(h, 0, d) + \Theta(k^2) ,
\]
where $T(1, 0, d) = \Theta(1)$ is the base case. The summation in this derivation represents the span due to spawning. A parallel for with $r$ iterations adds $\Theta(\lg r)$ to the span, and since the number of zoids at all levels is $3^k$, this value upper-bounds the number of iterations at any given level. Moreover, the lower bound on the number of zoids on a given level is at least the average $3^k/(k+1)$, whose logarithm is asymptotically the same as $\lg(3^k)$, and hence the bound is asymptotically tight.

A time cut can be applied when the zoid is minimal. Assume that $k \geq 0$ projection trapezoids $Z_0$’s are upright and the rest are inverted. Then for each upright projection trapezoid $Z_0$, the normalized width of the lower zoid generated by the hyperspace cut is $\hat{w}_i = h$, the same as for $Z$, and for each inverted projection trapezoid $Z_i$, the lower zoid has normalized width $\hat{w}_i - h/2 = h/2$. Similarly, for each upright projection trapezoid $Z_0$, the normalized width of the upper zoid is $\hat{w}_i - h/2 = h/2$, and for each inverted projection trapezoid $Z_i$, the upper zoid has normalized width $\hat{w}_i$. Thus, the recurrence for the span of $\text{TRAP}$ when a minimal $Z$ undergoes a time cut can be written as follows:

$$T_w(h, 0, d) = T_w(h/2, k, d-k) + T_w(h/2, d-k, k) + \Theta(1).$$

Applying hyperspace cuts to the subzoids on the right-hand side of this recurrence yields

$$T_w(h, 0, d) = (d+2)T_w(h/2, 0, d) + \Theta((d-k)^2)$$

$$= (d+2)T_w(h/2, 0, d) + \Theta(d^2)$$

$$= \Theta(d^2(d+2)^{\lg h^2}) + \Theta((d+2)^{\lg h})$$

$$= \Theta(d^2(d+2)^{\lg h}) + \Theta((d+2)^{\lg h}).$$

**Theorem 3.** Consider a $(d+1)$-dimensional grid $Z$ with $\hat{w}_i = w$ for $i \in \{0, \ldots, d-1\}$ and height $h = 2^w$. Then the parallelism of $\text{TRAP}$ when processing $Z$ using a stencil with constant slopes is $\Theta(w_d(d+2)^{\lg h}/d^2)$. 

**Proof.** Assume without loss of generality that the stencil is periodic. (As will be discussed in Section 4, Pochoir implements $\text{TRAP}$ so that the control structure for nonperiodic stencils is the same as that for periodic.) The algorithm first applies a series of $r$ time cuts, dividing the original time dimension into $h/w = 2^w$ subgrids with $\hat{w}_i = w$ with height $w$. These grids are processed serially. The next action of $\text{TRAP}$ applies a hyperspace cut to all $d$ spatial dimensions of $Z$, dividing the grid into $d+1$ minimal zoids which are then processed serially. Applying Lemma 2 yields a span of

$$T_w = (h/w)(d+1)\cdot \Theta(dw^{d+2})$$

$$= \Theta((d^2h)w^{d+2}) + \Theta((d+2)^{\lg h} - 1).$$

The work is the volume of $Z$, which is $T_1 = \Theta(hw^d)$, since the stencil has constant slopes. Thus, the parallelism is

$$T_1/T_w = \Theta(w_d(d+2)^{\lg h}/d^2).$$

We can compare $\text{TRAP}$ with a version of Frigo and Strumpen’s parallel stencil algorithm [17] we call $\text{STRAP}$, which performs the space cuts serially as in Figures 7(a) and 7(b). Each space cut results in one synchronization point, and hence a sequence of $k$ space cuts applied by $\text{STRAP}$ introduces $2^k$ parallel steps compared to the $k+1$ parallel steps generated by $\text{TRAP}$ (see Lemma 1). Thus, each space cut virtually doubles $\text{STRAP}$’s span. Figure 8(a) shows a simple example where $\text{STRAP}$ produces $2^2 - 1 = 3$ synchronization points while $\text{TRAP}$ introduces only 2. The next lemma and theorem analyze $\text{STRAP}$, mimicking Lemma 2 and Theorem 3. Their proofs are omitted.

**Lemma 4.** Consider a minimal $(d+1)$-zoid $Z$ with height $h$ and normalized widths $\hat{w}_i = h$ for $i \in \{0, 1, \ldots, d-1\}$. Then the span of $\text{STRAP}$ when processing $Z$ is $\Theta(h^{d+1}/d)$. 

**Theorem 5.** Consider a $(d+1)$-dimensional grid $Z$ with $\hat{w}_i = w$ for $i \in \{0, 1, \ldots, d-1\}$ and height $h = 2^w$. Then the parallelism of $\text{STRAP}$ when processing $Z$ using a stencil with constant slopes is $\Theta(w_d(d+2)^{\lg h}/d^2).$ 

**Discussion**

As can be seen from Theorems 3 and 5, both $\text{TRAP}$ and $\text{STRAP}$ have the same asymptotic parallelism $\Theta(w_d(d+2)^{\lg h}/d^2)$ for $d = 1$, but for $d = 2$, $\text{TRAP}$ has $\Theta(w^2)$ while $\text{STRAP}$ has $\Theta(w^3)$, and the difference grows with the number of dimensions.

The cache complexities of $\text{TRAP}$ and $\text{STRAP}$ are the same, which follows from the observation that both algorithms apply exactly the same time cuts in exactly the same order, and immediately before each time cut, both are in exactly the same state in terms of the spatial cuts applied. Thus, they arrive at exactly the same configuration — number, shape, and size — of subzoids before each time cut.

Frigo and Strumpen’s parallel stencil algorithm is actually slightly different from $\text{STRAP}$. For any fixed integer $r > 1$, a space cut in their algorithm produces $r$ black zoids and between $r-1$ and $r+1$ gray zoids. $\text{STRAP}$ is a special case of that algorithm with $r = 2$ for upright projection trapezoids and $r = 1$ for inverted projection trapezoids. For larger values of $r$, Frigo and Strumpen’s algorithm achieves more parallelism but the cache efficiency drops. It is straightforward to extend $\text{TRAP}$ to perform $r$ multiple cuts along each dimension to match the cache complexity of Frigo and Strumpen’s algorithm while providing asymptotically more parallelism.

**Empirical results**

Figure 9 shows the results of using the Cilkview scalability analyzer [20] to compare the parallelism of $\text{TRAP}$ and $\text{STRAP}$ on two typical benchmarks. We measured the two algorithms with uncoarsened base cases. As can be seen from the figure, $\text{TRAP}$’s asymptotic advantage in parallelism is borne out in practice for these benchmarks.

We used the Linux perf tool [29] to verify that $\text{TRAP}$ does not suffer any loss in cache efficiency compared to the $\text{STRAP}$ algorithm. Figure 10 also plots the cache-miss ratio of the straightforward parallel loop algorithm, showing that it exhibits poorer cache performance than the two cache-oblivious algorithms.

**4. COMPILER OPTIMIZATIONS**

The Pochoir compiler transforms code written in the Pochoir specification language into optimized C++ code that employs the Intel Cilk multithreading extensions [23]. The Pochoir compiler is written in Haskell [37], and it performs numerous optimizations, the most important of which are code cloning, loop-index calculations, unifying periodic and nonperiodic boundary conditions, and coarsening the base case of recursion. This section describes how the Pochoir compiler implements these optimizations.

Before a programmer compiles a stencil code with the Pochoir compiler, he or she is expected to perform Phase 1 of Pochoir’s two-phase methodology which requires that it be compiled using the Pochoir template library and debugged. This C++ template library is employed by both Phases 1 and 2 and includes both loop-based and trapezoidal algorithms. Differences between stencils, such as dimensionality or data structure, are incorporated into these generic algorithms at compile-time via C++ template metaprogramming.
Handling boundary conditions by code cloning

The handling of boundary conditions can easily dominate the run-time of a stencil computation. For example, we coded the 2D heat equation on a periodic torus using Pochoir, and we compared it to a comparable code that simply employs a modulo operation on every array index. For a 5000 \( \times \) 5000 spatial grid over 5000 time steps, the run-time of the modular-indexing implementation degraded by a factor of 2.3.

For nonperiodic stencil computations, where a value must be provided on the boundary, performance can degrade even more if a test is made at every point to determine whether the index falls off the grid. Stencil implementers often handle constant nonperiodic boundary conditions with the simple trick of introducing ghost cells \[8\] that form a halo around the periphery of the grid. Ghost cells are read but never written. The stencil computation can apply the kernel function to the grid points on the real grid, and accesses that “fall off” the edge into the halo obtain their values from the ghost cells without any need to check boundary conditions.

In practice, however, nonperiodic boundary conditions can be more complicated than simple constants, and we wanted to allow Pochoir users flexibility in the kinds of boundary conditions they could specify. For example, Dirichlet boundary conditions may specify boundary values that change with time, and Neumann boundary conditions may specify the value the derivative should take on the boundary \[14\]. Figure 11(a) shows a Pochoir specification of a Dirichlet boundary condition, and Figure 11(b) shows the Pochoir specification of a Neumann boundary condition.

To handle boundaries efficiently, the Pochoir compiler generates two code clones of the kernel function: a slower boundary clone and a faster interior clone. The boundary clone is used for boundary zoids: those that contain at least one point whose computation requires an off-grid access. The interior clone is used for interior zoids: those all of whose points can be updated without indexing.
Unifying periodic and nonperiodic boundary conditions

Typical stencil codes discriminate between periodic and nonperiodic stencils, implementing them in different ways. To make the specification of boundary functions as flexible as possible, we investigated how periodic and nonperiodic stencils could be implemented using the same algorithmic framework, leaving the choice of boundary function up to the user. Our unified algorithm allows the user to program boundary functions with arbitrary periodic/nonperiodic behavior, providing support, for example, for a 2D cylindrical domain, where one dimension is periodic and the other is nonperiodic.

The key idea is to treat the entire computation as if it were periodic in all dimensions and handle nonperiodicity and other boundary conditions in the base case of the boundary clone where the
kernel function is invoked. When a zoid wraps around the grid in a
given dimension $i$, meaning that $x_{ai} > x_{bi}$, we represent the lower-
and upper-bound coordinates of the zoid in dimension $i$ by virtual
coordinates $(x_{ai}, N_i + x_{bi})$, where $N_i$ is the size of the periodic grid
in dimension $i$. In the base of the recursion of the boundary clone,
Pochoir calls the kernel function and supplies it with the true co-
ordinates of the grid point being updated by performing a modulo
computation on each coordinate. Within the kernel function, ac-
tesses to the Pochoir arrays now call the boundary function, which
provides the correct value for grid points that are outside the true
grid. Of course, no such checking is required for interior zoids,
which are always represented by true coordinates.

**Coarsening of base cases**

Previous work [9, 26, 27, 34] has found that although trapezoidal
decomposition dramatically reduces cache-miss rates, overall per-
formance can suffer from function-call overhead unless the base
case of the recursion is coarsened. For example, proper coarsen-
ing of the base case of the 2D heat-equation stencil (running for
5000 time steps on a $5000 \times 5000$ toroidal grid) improves the per-
formance by a factor of 36 over running the recursion down to a
single grid point.

Since choosing the optimal size of the base case can be difficult,
we integrated the ISAT autotuner [22] into Pochoir. Despite the
advantage of finding the optimal coarsening factor on any specific
platform, this autotuning process can take hours to find the optimal
value, which may be unacceptable for some users.

In practice, Pochoir employs some heuristics to choose a rea-
sonable coarsening. One principle is that to maximize data reuse,
we want to make the spatial dimensions all about the same size.
Another principle is that to exploit hardware prefetching, we want
to avoid cutting the unit-stride spatial dimension and avoid odd-
shaped base cases. For example, for 2D problems, a square-shaped
computing domain often offers the best performance. We have
found that for 3D problems, the effect of hardware prefetching
can often be more important than cache efficiency for reasonably
sized base cases. Consequently, for 3 or more dimensions, Pochoir
adopts the strategy of never cutting the unit-stride spatial dimen-
sion, and it cuts the rest of the spatial dimensions into small hyper-
cubes to ensure that the entire base case stays in cache. Given all
that potential complexity, the compiler’s heuristic is actually fairly
simple. For 2D problems, Pochoir stops the recursion at $100 \times 100$
space chunks with 5 time steps. For 3D problems, the recursion
stops at $1000 \times 3 \times 3$ with 3 time steps.

5. **RELATED WORK**

Attempts to compile stencils into highly optimized code are not new.
This section briefly reviews the history of stencil compilers and
discusses some of the more recent innovative strategies for opti-
mitizing stencil codes.

Special-purpose stencil compilers for distributed-memory ma-
achines first came into existence at least two decades ago [3, 4, 39].
The goal of these researchers was generally to reduce interpro-
sessor data transfer and improve the performance of loop-based stencil
computations through loop-level optimizations. The compilers ex-
pected the stencils to be expressed in some normalized form.

More recently, Krishnamoorthy et al. [28] have considered au-
tomatic parallelization of loop-based stencil codes through loop
tiling, focusing on load-balancing the execution of the tiles. Kamil
et al. [25] have explored automatic parallelization and tuning of
stencil computations for chip multiprocessors. The stencils are
specified using a domain-specific language which is a subset of For-
tran 95. An abstract syntax tree is built from the stencil specified in
the input language, from which multiple formats of output can be
generated, including Fortran, C, and CUDA. The parallelization is
based on blocked loops.

We have discussed Frigo and Strumpen’s seminal trapezoidal-
decomposition algorithms [16, 17] at length, since they form the
foundation of the Pochoir algorithm. Nitsure [34] has studied how
to use Frigo and Strumpen’s parallel algorithm to implement 2D
and 3D lattice Boltzmann methods. In addition to several other
optimizations, Nitsure employs two code clones for the kernel to
reduce the overhead of boundary checking, which Pochoir does as
well. Nitsure’s stencil code is parallelized with OpenMP [35], and
data dependencies among subdomains are maintained by locking.

Cache-aware techniques have been used extensively to improve
the stencil performance. Datta et al. [9] and Kamil et al. [26, 27]
have applied both algorithmic and coding optimizations to loop-
based stencil computations. Their algorithmic optimizations in-
clude an explicitly blocked time-skewing algorithm which overlaps
subregions to improve parallelism at the cost of redundant mem-
ory storage and computation. Their coding optimizations include
processor-affinity binding, kernel inlining, an explicit user stack,
early cutoff, indirection instead of modulo, and autotuning.

Researchers at the University of Southern California [11, 12, 36]
have performed extensive studies on how to improve the perfor-
mance of high-order stencil computations though parallelization
and optimization. Their techniques, which apply variously to mul-
ticore and cluster machines, include intranode, internode, and data-
parallel optimizations, such as cache blocking, register blocking,
manual SIMD-izing, and software prefetching.

6. **CONCLUDING REMARKS**

It is remarkable how complex a simple computation can be when
performance is at stake. Parallelism and caching make stencil com-
putations interesting. As discussed in Section 5, many researchers
have investigated how various other features of modern machines
— such as prefetching units, graphical processing units, and clus-
tering — can be exploited to provide even more performance. We
see many ways to improve Pochoir by taking advantage of these
machine capabilities.

In addition, we see ample opportunity to enhance the lingu-
istic features of the Pochoir specification language to provide more
generality and flexibility to the user. For example, we are con-
sidering how to allow the user to specify irregularly shaped do-
 mains. As long as the boundary of a region, however irregular, is
small compared to the region’s interior, special-case code to handle
the boundary should not adversely impact the overall performance.
Even more challenging is coping with boundaries that change with
time. We believe that such capabilities will dramatically speed up
the PSA, RNA, and LCS benchmarks which operate on diamond-
shaped space-time domains.

Pochoir’s two-phase compilation strategy introduces a new
method for building domain-specific languages embedded in C++. His-
torically, the complexity of parsing and type-checking C++
has impeded such separately compiled domain-specific languages.
C++’s template programming does provide a good measure of ex-
pressiveness for describing special-purpose computations, but it
provides no ability to perform the domain-specific optimizations
such as those that Pochoir employs. Pochoir’s compilation strategy
offers a new way to build optimizing compilers for domain-specific
languages embedded in C++ where the compiler can parse and “un-
derstand” only as much of the programmer’s C++ code as it is able,
confident that code it does not understand is nevertheless correct.

The Pochoir compiler can be downloaded from http://
supertech.csail.mit.edu/pochoir.
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8. REFERENCES