

Compilation and Backend-Independent Vectorization for Multi-Party Computation

Benjamin Levy
levyb3@rpi.edu
Rensselaer Polytechnic Institute
Troy, New York

Lindsey Kennard
fireelemental.ne@gmail.com
STR
Boston, Massachusetts

Benjamin Sherman
shermb@rpi.edu
Rensselaer Polytechnic Institute
Troy, New York

Ana Milanova
milanova@cs.rpi.edu
Rensselaer Polytechnic Institute
Troy, New York

Muhammad Ishaq
ishaqm@purdue.edu
Purdue University
West Lafayette, Indiana

Vassilis Zikas
vzikas@purdue.edu
Purdue University
West Lafayette, Indiana

ABSTRACT

ANA: *We need an abstract.*

CCS CONCEPTS

• Theory of computation → Program analysis; Cryptographic protocols; • Security and privacy → Cryptography.

KEYWORDS

multiparty computation; compilers; cryptography

ACM Reference Format:

Benjamin Levy, Benjamin Sherman, Muhammad Ishaq, Lindsey Kennard, Ana Milanova, and Vassilis Zikas. 2019. Compilation and Backend-Independent Vectorization for Multi-Party Computation. In *2019 ACM SIGSAC Conference on Computer and Communications Security (CCS '19)*, November 11–15, 2019, London, United Kingdom. ACM, New York, NY, USA, ?? pages. <https://doi.org/10.1145/3319535.3339818>

1 INTRODUCTION

Multi-party computation (MPC) allows N parties p_1, \dots, p_N to perform a computation on their private inputs securely. Informally, security means that the secure computation protocol computes the correct output (correctness) and it does not leak any information about the individual party inputs, other than what can be deduced from the output (privacy).

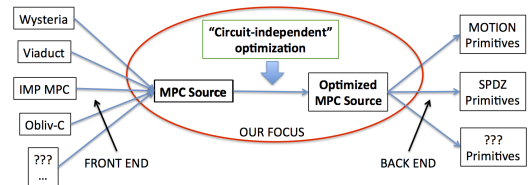
MPC theory dates back to the early 1980-ies [?, ?, ?, ?]. Long the realm of theoretical cryptography, MPC has seen significant advances in programming technology in recent years. These advances bring MPC closer to practice and wider applicability — MPC technology has been employed in

real-world scenarios such as auctions [?], biometric identification [?], and privacy-preserving machine learning [?, ?]. The goal is to bring the technology to a level where programmers can write *secure* and *efficient* programs without commanding extensive knowledge of cryptographic primitives.

The problem, therefore, is to build a high-level programming language and a compiler, and there has been significant advance in this space, e.g., [?, ?, ?, ?, ?, ?] among other work. Current research largely falls at the two ends of the classical compiler: (1) work on *front-end* language design and (2) work on *back-end* protocol implementation. Work on language design focuses on high-level constructs necessary to express multiple parties, computation by different parties, and information flow from one party to another [?, ?]. On the other end, work on protocol implementation focuses on cryptographic foundations and their efficient circuit-level implementation [?, ?, ?], e.g., implementation of operations (e.g., MUL, ADD) using different sharing protocols (Boolean or Arithmetic GMW [?] or Yao’s garbled circuits [?]), as well as efficient share conversion from one representation to another.

Earlier compilers did both back-end and front-end translation without a specific focus on either, as their aim was to demonstrate applicability of MPC on real-world programming problems. As the field advanced, works have focused more closely on front-end language design (e.g., Wysteria [?] and Viaduct [?]) or back-end “circuit-level” design and implementation (e.g., MOTION [?]).

In this work we focus on an intermediate language and what we call *backend-independent optimizations*, in a close analogy to *machine-independent* optimizations in the classical compiler. The following figure summarizes our key idea:



We emphasize the MPC Source intermediate representation and optimization over MPC Source. As in classical compilers, we envision different front ends (e.g., Wysteria, our front

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

CCS '19, November 11–15, 2019, London, United Kingdom

© 2019 Association for Computing Machinery.

ACM ISBN 978-1-4503-6747-9/19/11...\$15.00

<https://doi.org/10.1145/3319535.3339818>

end IMP-MPC) compiling into MPC Source. MPC Source is particularly suitable for optimizations such as protocol mixing [?, ?] and SIMD-vectorization, which takes advantage of amortization at the circuit level. The MPC Source IR exposes the linear structure of MPC programs, which simplifies program analysis; this is in contrast to source, which has if-then-else constructs. In the same time, MPC Source is sufficiently “high-level” to support analyses and optimizations that take into account control and data flow in a specific program. MPC Source is small in size and analysis is tractable, as opposed to analysis over an unrolled circuit [?]. Again as in classical compilers, we envision translation of MPC Source (optimized or unoptimized) into MOTION, SPDZ, or other back-end code.

1.1 Our Contribution

In this paper, we develop a compiler framework that takes a Python-like routine and produces MOTION code: we describe (a) the IMP-MPC language, its syntax and semantic restrictions, (b) translation from IMP-MPC into MPC Source, (c) a specific backend-independent optimization: novel SIMD-vectorization on MPC Source, and (d) translation from MPC Source into MOTION code.

We focus on the MOTION framework as our back-end for several reasons. First, it is the state of the art in terms of performance [?]. Second, it provides an API over efficient implementation for a wide variety of cryptographic operations in three different protocols — Arithmetic GMW, Boolean GMW, and BMR — which allows for protocol mixing [?, ?], a known backend-independent optimization. Third, MOTION provides API for SIMD-level operations, which amortize cost and lead to significant improvement in memory footprint and throughput [?, ?, ?]. It enables MPC Source-level vectorization, a key focus of this paper.

Our second contribution is an analytical model for cost estimation of amortized schedules. Originally, we hoped that optimal scheduling (under our model) was tractable, as the problem appeared simpler than the classical scheduling problem. Unfortunately, we show that optimal scheduling is NP-hard via a reduction to the Shortest Common Supersequence (SCS) problem. Cost modeling is important as it drives not only vectorization but optimizations such as protocol mixing and scheduling as well [?, ?].

Our most important contribution is the implementation and evaluation of the compiler framework. We demonstrate expressivity of the source language by running the compiler on **ANA: X** programs; these include classical MPC benchmarks such as PSI and Biometric matching, as well as kMeans, Histogram, and others. **ANA: Summarize results.**

Our results emphasize the importance of backend-independent optimizations — vectorization (described in this work) and protocol mixing (tackled in previous works [?, ?, ?]) are two optimizations readily available at the level of MPC Source. We believe that our work can lead to future work on backend-independent compilation and optimization, ushering new MPC optimizations and combinations of optimizations in the vein of standard compilers, and thus bringing MPC

programming technology closer to practice and wider applicability.

1.2 Outline

The rest of the paper is organized as follows. §?? presents an overview of the compiler. §?? describes our model for cost estimation and argues NP-hardness of optimal scheduling. §?? details the front-end phases of the compiler, §?? focuses in on backend-independent vectorization, and §?? describes translation into MOTION. §?? presents the experimental evaluation. §?? discusses related work and §?? concludes.

2 OVERVIEW

2.1 Source

As a running example, consider Biometric matching, a standard MPC benchmark. An intuitive (and naive) implementation is as shown in Listing ??(a). Array **C** is the feature vector of **D** features that we wish to match and **S** is the database of **N** size-**D** vectors that we match against.

Our compiler takes essentially standard IMP **ANA: Need citation here.** syntax and imposes certain semantic restrictions. (We detail the restrictions in the following sections.) The programmer writes an iterative program and annotates certain inputs and outputs as *shared*. In the example arrays **C** and **S** are *shared*, meaning that they store shares, however, the array sizes **D** and **N** respectively are plaintext. The code iterates over the entries in the database and computes the Euclidean distance of the current entry **S[i]** and **C** (its square actually). The program returns the index of the vector that gives the best match plus the corresponding sum of squares.

2.2 MPC Source and Cost of Schedule

Our compiler generates an intermediate representation, MPC Source. MPC Source for Biometric Matching is shown in Listing ??(b). First, MPC Source is an SSA form. Second, it is linear. The conditional in lines 13-14 in IMP Source turns into the linear code in lines 12-16 in MPC Source. The test turns into the CMP operation $t = \text{CMP}(\text{sum!3}, \text{min_sum!2})$, followed by the true-branch sequence, followed by the MUX operations. The first MUX operation selects the value of **min_sum**: if **t** is true, then **min_sum** gets the value of the second multiplexer argument, **min_sum!3**, otherwise it takes the value of the third argument, **min_sum!2**. Third, MPC Source is a special form of SSA. The SSA ϕ -nodes at the if-then-else (lines 13-15) turn into MUX operations, while the ϕ -nodes at for-loops turn into *pseudo* PHI nodes with a straightforward semantics.

We turn to our analytical model to compute the *cost* of the iterative program. Assuming cost β for a local MPC operation (essentially just ADD) and cost α for a remote MPC operation (e.g., MUX, CMP, and remaining operations), the cost of the iterative schedule will be $ND(2\alpha + \beta) + N(3\alpha)$.

A key contribution is the vectorizing transformation. We can compute all $N * D$ subtraction operations (line 9 in (b)) in a single SIMD instruction; similarly we can compute all

```

1 def biometric(C: shared[list[int]], D: int,
2   S: shared[list[int]], N: int) ->
3   shared[tuple[int,int]]:
4   min_sum : int = MAX_INT
5   min_idx : int = 0
6   for i in range(N):
7     sum : int = 0
8     for j in range(D):
9       # d = S[i,j] - C[j]
10      d : int = S[i * D + j] - C[j]
11      p : int = d * d
12      sum = sum + p
13      if sum < min_sum:
14        min_sum : int = sum
15        min_idx : int = i
16  return (min_sum, min_idx)

```

(a) IMP Source

```

1 min_sum!1 = MAX_INT
2 min_idx!1 = 0
3 for i in range(0, N):
4   min_sum!2 = PHI(min_sum!1, min_sum!4)
5   min_idx!2 = PHI(min_idx!1, min_idx!4)
6   sum!2 = 0
7   for j in range(0, D):
8     sum!3 = PHI(sum!2, sum!4)
9     d = SUB(S[(i * D) + j], C[j])
10    p = MUL(d,d)
11    sum!4 = ADD(sum!3,p)
12    t = CMP(sum!3,min_sum!2)
13    min_sum!3 = sum!3
14    min_idx!3 = i
15    min_sum!4 = MUX(t, min_sum!3, min_sum!2)
16    min_idx!4 = MUX(t, min_idx!3, min_idx!2)
17  return (min_sum!2, min_idx!2)

```

(b) MPC Source

```

1 min_sum!1 = MAX_INT
2 min_idx!1 = 0
3 # S^ is same as S. C^ replicates C N times:
4 S^ = raise_dim(S, ((i * D) + j), (i:N,j:D)) #S^[i,j] = S[i,j]
5 C^ = raise_dim(C, j, (i:N,j:D)) #C^[i,j] = C[j]
6
7 sum!2[l] = [0,...,0]
8 # computes _all_ "at once"
9 d[l,J] = SUB_SIMD(S^[l,J],C^[l,J])
10 p[l,J] = MUL_SIMD(d[l,J],d[l,J])
11
12 for j in range(0, D):
13   # sum!2[l], sum!3[l], sum!4[l] are size-N vectors
14   # computes N intermediate sums "at once"
15   sum!3[l] = PHI(sum!2[l], sum!4[l])
16   sum!4[l] = ADD_SIMD(sum!3[l],p[l,j])
17
18 min_idx!3[l] = [0,1,...,N-1]
19 for i in range(0, N):
20   min_sum!2 = PHI(min_sum!1, min_sum!4)
21   t[i] = CMP(sum!3[i],min_sum!2)
22   min_sum!4 = MUX(t[i], sum!3[i], min_sum!2)
23   for i in range(0, N):
24     min_idx!2 = PHI(min_idx!1, min_idx!4)
25     min_idx!4 = MUX(t[i], min_idx!3[i], min_idx!2)
26  return (min_sum!2, min_idx!2)

```

(c) Optimized MPC Source

Table 1: Biometric Matching: From IMP Source to MPC Source to Optimized MPC Source. *ANA: Add explanation to caption, this is hard to see.*

multiplication operations (line 10) in a single SIMD instruction. And while computation of an individual sum remains sequential, we can compute the N sums in parallel. Our compiler *automatically detects these opportunities and transforms the program*. It is standard that MPC researchers write vectorized versions of the Biometric program by hand; we are the first (to the best of our knowledge) to automatically transform a naive, iterative MPC program into an unintuitive vectorized one.

2.3 Vectorized MPC Source and Cost of Schedule

Our compiler produces the vectorized program shown in Listing ??(c). Note that this is still our intermediate representation, Optimized MPC Source. Subsequently, the compiler turns this code into MOTION variables, loops and SIMD primitives, which MOTION then uses to generate the circuit.

The compiler determines that SUB and MUL in “naive” MPC Source (lines 9 and 10 in (b)) can be fully vectorized into the SIMD SUB and MUL in optimized MPC Source (lines 9 and 10 in (c)). Notation $p[l,j]$ denotes a 2-dimensional array with fully vectorized dimensions. The computation of sum (line 11 in (b)) is sequential across the j -dimension, but it is parallel across the i -dimension. The loop in lines 12-16

in (c) illustrates; here $p[l,j]$ refers to the j -th column in p . Unfortunately, CMP and MUX remain sequential.

In MPC backends, executing n operations “at once” in a single SIMD operation costs a lot less than executing those n operations one by one. This is particularly important when there is communication (i.e., in remote), since many 1-bit values are sent at once rather than sequentially. We elaborate on the cost model in Section §?? but for now consider that each operation has a *fixed* portion (does benefits from amortization) and a *variable* portion (does not benefit from amortization): $\alpha = \alpha_{fix} + \alpha_{var}$. This gives rise to the following formula for amortized cost: $f(n) = \alpha_{fix} + n\alpha_{var}$, as opposed to unamortized cost $g(n) = n\alpha_{fix} + n\alpha_{var}$. (We extend the same reasoning to β -instructions.)

Thus, the fixed cost of the vectorized program amounts to $2\alpha_{fix} + D\beta_{fix} + N(3\alpha_{fix})$. (The variable cost is the same in both the vectorized and non-vectorized programs.) The first term in the sum corresponds to the vectorized subtraction and multiplication (lines 9-10 in (c)), the second term corresponds to the FOR loop on j (lines 12-16) and the third one corresponds to the remaining FOR loops on i (lines 19-25). Clearly, $2\alpha_{fix} + D\beta_{fix} + N(3\alpha_{fix}) \ll ND(2\alpha_{fix} + \beta_{fix}) + N3\alpha_{fix}$. Empirically, we observe 10x to 50x improvement over unvectorized Biometric Matching in circuit generation time and

setup time and 5x to 30x improvement in online time. Additionally, the un-vectorized version runs out of memory for $N = 256$, while the vectorized one runs with the standard maximal input size $N = 4,096$. *ANA: Edit numbers with final experiments.*

3 ANALYTICAL MODEL

ANA: Terminology: "operation" or "instruction" or "gate"?

This section presents a model to reason about the cost of execution of MPC programs, including accounting for amortization. We define the assumptions and setting in §???. We proceed to define the scheduling problem in §??, which we expected to be able to solve optimally. §?? shows that the problem is NP-hard via a reduction to the Shortest Common Supersequence (SCS) problem. Despite the negative general result, we expect the formulation in terms of SCS to be useful as sequences are short and few in practice.

3.1 Scheduling in MPC

For this treatment we make the following simplifying assumptions:

- (1) All statements in the program execute using the same protocol (sharing). That is, there is no share conversion.
- (2) There are two tiers of MPC instructions, local and remote. A local instruction (essentially just ADD) has cost β and a remote instruction (e.g., MUX, MUL, SHL, etc.) has cost α , where $\alpha \gg \beta$. We assume that all remote instructions have the same cost.
- (3) In MPC frameworks, executing n operations "at once" in a single SIMD operation costs a lot less than executing those n operations one by one. Following Amdahl's law *ANA: citation!*, we write $\alpha = \frac{1}{s}p\alpha + (1-p)\alpha$, where p is the fraction of execution time that benefits from amortization and $(1-p)$ is the fraction that does not, and s is the available resource. Thus, $n\alpha = \frac{n}{s}p\alpha + n(1-p)\alpha$. For the purpose of the model we assume that s is large enough and the term $\frac{n}{s}p\alpha$ amounts to a *fixed cost* incurred regardless of whether n is 10,000 or just 1. (This models the cost of preparing and sending a packet from party A to party B for example.) Therefore, amortized execution of n operations is $f(n) = \alpha_{fix} + n\alpha_{var}$ in contrast to unamortized execution $g(n) = n\alpha_{fix} + n\alpha_{var}$ and, of course. Clearly $\alpha_{fix} \ll n\alpha_{fix}$ and since fixed cost dominates variable cost (particularly for remote operations), we have $f(n) \ll g(n)$.
- (4) MPC instructions scheduled in parallel benefit from amortization *only if* they are the same instruction. Given our previous assumption, 2 MUL instructions can be amortized in a single SIMD instruction that costs $\alpha_{fix} + 2\alpha_{var}$, however a MUL and a MUX instruction still cost $2\alpha_{fix} + 2\alpha_{var}$ even when scheduled "in parallel".¹

¹This is not strictly true, but assuming it, e.g. as in [?, ?, ?], helps simplify the problem.

3.2 Problem Statement

As mentioned earlier, at the lowest level, we have two types of MPC instructions (also called *gates* in similar works) 1) local/non-interactive instruction (i.e. an addition instruction A) and 2) remote/interactive instruction (i.e. a multiplication instruction M).

Given a serial schedule (a linear graph) of an MPC program i.e. a sequence of instructions $S := (S_1; \dots; S_n)$, where $S_i \in \{A, M\}$, $1 \leq i \leq n$, and a def-use dependency graph $G(V, E)$ corresponding to S , our task is to construct a parallel schedule (another linear graph) $P := (P_1; \dots; P_m)$ observing the following conditions:

- (1) All P_i 's consist of MPC instructions of the same kind, e.g., all MUL, MUX, ADD, etc.
- (2) Def-use dependencies of the graph $G(V, E)$ should be preserved i.e. if instructions S_i, S_j , $i < j$ form a def-use i.e. an edge exists from S_i to S_j in G , then they can only be mapped to $P_{i'}, P_{j'}$ such that $i' < j'$.

Correctness. Correctness of P is guaranteed by definition. Preserving def-use *dependencies* means the computed function remains the same in both S and P .

The cost of schedule S is

$$cost(S) = \sum_{i=1}^n cost(S_i) = L_\alpha \alpha_{fix} + L_\beta \beta_{fix} + L_\alpha \alpha_{var} + L_\beta \beta_{var} \quad (1)$$

where L_α is the number of α -instructions and L_β is the number of β ones. (We used this formula to compute the cost of the unrolled MPC Source program in §??.) The cost of schedule P is more interesting:

$$cost(P) = \sum_{i=1}^m cost(P_i) \quad (2)$$

Each P_i may contain multiple instructions, and $cost(P_i)$ is amortized. Thus, according to our model $cost(P_i) = \alpha_{fix} + |P_i| \alpha_{var}$ if P_i stores $|P_i|$ α -instructions, or $cost(P_i) = \beta_{fix} + |P_i| \beta_{var}$ if it stores β -instructions. (Similarly, we used this formula to compute the cost of the Optimized MPC Source program in §??.)

Our goal is to construct a parallel schedule P that reduces the program cost (when compared to cost of S), possibly an optimal schedule. Originally we hoped that the problem is simpler and computation of the optimal schedule is tractable. Unfortunately, the optimal schedule turns out to be NP-hard via a reduction to the Shortest Common Supersequence problem.

3.3 Scheduling is NP-hard

To prove that optimal scheduling is an NP-Hard problem, we consider the following convenient representation. An MPC program is represented as a set of sequences $\{s_1, \dots, s_n\}$ of operations. In each sequence s_i operations depend on previous operations via a def-use i.e. $s_i[j]$, $j > 1$ depends on $s_i[j-1]$.

As an example, consider the MPC program consisting of the following three sequences, all made up of two distinct

α -instructions M_1 and M_2 , e.g., M_1 is MUL and M_2 is MUX. The right arrow indicates a def-use *dependence*, meaning that the source node must execute before the target node:

- (1) $M_1 \rightarrow M_2 \rightarrow M_1$
- (2) $M_1 \rightarrow M_1 \rightarrow M_1$
- (3) $M_2 \rightarrow M_1 \rightarrow M_2$

The problem is to find a schedule P with *minimal cost*. For example, a schedule with minimal cost for the sequences above is

$M_1(1), M_1(2); M_1(2); M_2(1), M_2(3); M_1(1), M_1(2), M_1(3); M_2(3)$

The parentheses above indicate the sequence where the instruction comes from: (1), (2), or (3). Cost of schedule P is computed using ?? above and it amounts to $5\alpha_{fix} + 9\alpha_{var}$.

The problem of finding a schedule P with a minimal $cost(P)$ is shown to be NP-Hard problem, as it can be reduced to the problem of finding a *shortest common supersequence*, a known NP-Hard problem[?, ?]. The shortest common supersequence problem is as follows: *given two or more sequences find the the shortest sequence that contains all of the original sequences*. This can be solved in $O(n^k)$ time, where n is the cardinality of the longest sequence and k is the number of sequences. We can immediately see that the optimal schedule is the shortest schedule, since the shortest schedule minimizes the fixed cost while the variable cost remains the same.

To formalize the reduction, suppose P is a schedule with minimal cost (computed by a black-box algorithm). Clearly P is a supersequence of each sequence s_i , i.e., P is a common supersequence of $s_1 \dots s_n$. It is also a shortest common supersequence. The cost of $cost(P) = L\alpha_{fix} + N\alpha_{var}$ where L is the length of P and N is the total number of instructions across all sequences. Now suppose, there exist a shorter common supersequence P' of length L' . $cost(P') < cost(P)$ since $L'\alpha_{var} + N\alpha_{var} < L\alpha_{var} + N\alpha_{var}$, contradicting the assumption that P has the lowest cost. \square

4 COMPILER FRONT END

ANA: Convention: use *shared*, *plain*, *code*, *i* and *I* for counters outside of code.

Fig. ?? presents an overview of our compiler. We start the section with a brief description of the top-level syntax and semantic restrictions in §???. We proceed to describe the front end of the compiler: §??? describes translation from IMP Source to SSA, and §??? describes translation from SSA into MPC Source.

We describe analysis on MPC Source and backend-independent vectorization in §??? and translation into MOTION code in §???.

4.1 Syntax and Semantic Restrictions

Source syntax is essentially standard IMP syntax as shown below:

$e ::= e \text{ op } e \mid e \mid x \mid \text{const} \mid A[e]$	<i>expression</i>
$s ::= s; s \mid$	<i>sequence</i>
$x = e \mid A[e] = e \mid$	<i>assignment stmt</i>
for i in $\text{range}(I) : s \mid$	<i>for stmt</i>
if $e : s$ else s	<i>if stmt</i>

The syntax allows for array accesses, arbitrarily nested loops, and if-then-else control flow. Expressions are typed $\langle q \tau \rangle$, where qualifier q and type τ are:

$\tau ::= \text{int} \mid \text{bool} \mid \text{list}[\text{int}] \mid \text{list}[\text{bool}]$	<i>base types</i>
$q ::= \text{shared} \mid \text{plain}$	<i>qualifiers</i>

The type system is mostly standard, and in our experience, a sweet spot between readability and expressivity. The **shared** qualifier denotes shared values, i.e., ones shared among the parties and computed upon under secure computation protocols; the **plain** qualifier denotes plaintext values. Shared lists denote shared elements, but plaintext length. Subtyping is **plain** $<:$ **shared**, meaning that we can convert a plaintext value into a shared one, but not vice versa. Subtyping on qualified types is again as expected, it is covariant in the qualifier and invariant in the type: $\langle q_1 \tau_1 \rangle <: \langle q_2 \tau_2 \rangle$ iff $q_1 <: q_2$ and $\tau_1 = \tau_2$.

Our compiler imposes certain semantic restrictions that it enforces throughout the various phases of compilation. We note that in some cases, the restrictions can be easily lifted and we plan to do so in future iterations of the work.

- (1) Loops are of the form $0 \leq i < I$ and bounds are fixed at compile time. It is a standard restriction in MPC that the bounds must be known at circuit-generation time.
- (2) Arrays are one-dimensional. N -dimensional arrays are linearized and accessed in row-major order and at this point the programmer is responsible for linearization and access. (This restriction can be easily lifted.)
- (3) Array subscripts are plaintext values as specified by the rule:

$$\frac{\Gamma \vdash e : \langle \text{plain int} \rangle \quad \Gamma \vdash A : \langle q \text{ list}[\tau] \rangle \quad \tau \in \{\text{int}, \text{bool}\}}{\Gamma \vdash A[e] : \langle q \tau \rangle} \quad (\text{ARRAY ACCESS})$$

The subscript e is a function of the indices of the enclosing loops. For read access, the compiler allows an arbitrary such function. However, it restricts write access to *canonical writes*, i.e., $A[i, j, k] = \dots$ where i, j and k loop over the three dimensions of A . Write access such as for example $A[i, j + 2] = \dots$ is not allowed.

- (4) The final restriction involves MUX as expressed by the rule:

$$\frac{\Gamma \vdash e_1 : \langle q_1 \text{ bool} \rangle \quad \Gamma \vdash e_2 : \langle q_2 \tau \rangle \quad \Gamma \vdash e_3 : \langle q_3 \tau \rangle \quad \tau \in \{\text{int}, \text{bool}\}}{\Gamma \vdash \text{MUX}(e_1, e_2, e_3) : \langle q_1 \vee q_2 \vee q_3 \tau \rangle} \quad (\text{MUX})$$

Importantly, the arguments of MUX are restricted to base types, as passing array arguments is not valid MOTION MPC. **ANA: Check this.** This causes a slight inconvenience as we could not write

```
1 if e: A[i] = val
```

Instead we had to write



Figure 1: Compiler Framework.

```

1 if not(e): val = A[i]
2 A[i] = val

```

We note that while the programmer writes annotations at the level of IMP Source (as in Listing ??(a)), the annotations propagate through the transformations and are checked at the level of MPC Source. Recall that the programmer annotates only inputs

For the rest of this section we write i, j, k to denote the loop nest: i is the outermost loop, j , is immediately nested in i , and so on until k and we use I, J, K to denote the corresponding upper bounds. We write $A[i, j, k]$ to denote canonical access to an array element. In the program, canonical access is achieved via the standard row-major order formula: $(J * K) * i + K * j + k$. To simplify the presentation we describe our algorithms in terms of three-element tuples i, j, k , however, discussion easily generalizes to arbitrarily large loop nests.

4.2 From IMP Source to SSA

Our compiler translates from Source to SSA as follows:

Parsing: Use Python’s `ast` module to parse the input source code to a Python AST.

Syntax checking: Ensure that the AST matches the restricted subset defined in Section §??. This step outputs an instance of the `restricted_ast.Function` class, which represents our restricted subset of the Python AST.

3-address CFG conversion: Convert the restricted-syntax AST to a three-address control-flow graph. To do this, first, add an empty basic block to the CFG and mark it as current. Next, for each statement in the restricted AST’s function body, process the statement. Statements can either be for-loops, if-statements, or assignments (as in §??). Rules for processing each kind of statement are given below:

- (1) **For-loops:** Create new basic blocks for the loop condition (the *condition-block*), the loop body (the *body-block*), and the code after the loop (the *after-block*). Insert a jump from the end of the current block to the condition-block. Then, mark the condition-block as the current block. Insert a for-instruction at the end of the current block with the loop counter variable and bounds from the AST. Next, add an edge from the current block to the after-block labeled “FALSE”

and an edge from the current block to the body-block labeled “TRUE”. Then, set the body-block to be the current block and process all statements in the AST’s loop body. Finally, insert a jump to the condition-block and set the after-block as current.

- (2) **If-statements:** Create new basic blocks for the “then” statements of the if-statement (the *then-block*), the “else” statements of the if-statement (the *else-block*), and the code after the if-statement (the *after-block*). At the end of the current block, insert a conditional jump to the then-block or else-block depending on the if-statement condition in the AST. Next, mark the then-block as current, process all then-statements, and add a jump to the after-block. Similarly, mark the else-block as current, process all else-statements, and add a jump to the after-block. Finally, set the after-block to be the current block, and give it a *merge condition* property equal to the condition of the if-statement.
- (3) **Assignments:** In the restricted-syntax AST, the left-hand side of assignments can be a variable or an array subscript. If it is an array subscript, e.g., $A[i] = x$, change the statement to $A = \text{Update}(A, i, x)$. If the statement is not already three-address code, for each sub-expression in the right-hand side of the assignment, insert an assignment to a temporary variable.

SSA conversion. : Convert the 3-address CFG to SSA with Cytron’s algorithm.

4.3 From SSA to MPC Source

Once the compiler converts the code to SSA, it transforms ϕ -nodes that correspond to if-statements into MUX nodes. From the 3-address CFG conversion step, ϕ -nodes corresponding to if-statements will be in a basic block with the merge condition property. For example, if $X!3 = \phi(X!1, X!2)$ is in a block with merge condition C , the compiler transforms it into $X!3 = \text{MUX}(C, X!1, X!2)$. Next, the compiler runs the dead code elimination algorithm from Cytron’s SSA paper.

Next, the control-flow graph is *linearized* into MPC Source, which has loops but no if-then-else-statements. This means that both branches of all if-statements are executed, and the MUX nodes determine whether to use results from the then-block or from the else-block. The compiler linearizes the control-flow graph with a variation of breadth-first search.

Blocks with the “merge condition” property are only considered the second time they are visited, since that will be after both branches of the if-statement are visited. (The Python AST naturally gives rise to a translation where each conditional has exactly two targets, and each “merge condition” block has exactly two incoming edges, a TRUE and a FALSE edge. Thus, each ϕ -node has exactly two multiplexer arguments, which dovetails into MUX. This is in contrast with Cytron’s algorithm which operates at the level of the CFG and allows for ϕ -nodes with multiple arguments.) Each time the compiler visits a block, it adds the block’s statements to the MPC source. If the block ends in a for-instruction, the compiler recursively converts the body and code after the loop to MPC source and adds the for-loop and code after the loop to the main MPC source. If the block does not end in a for-instruction, the compiler recursively converts all successor branches to MPC source and appends these to the main MPC source.

Now, the remaining ϕ -nodes in MPC source are the loop header nodes. We call these nodes *pseudo ϕ -nodes* and we write PHI in MPC Source. A pseudo ϕ -node $X!1 = \text{PHI}(X!0, X!2)$ in a loop header is evaluated during circuit generation. If it is the 0-th iteration, then the ϕ -node evaluates to $X!0$, otherwise, it evaluates to $X!2$.

5 BACKEND-INDEPENDENT VECTORIZATION

This section describes our vectorization algorithm. While vectorization is a longstanding problem, and we build upon existing work on scalar expansion and classical loop vectorization [?], our algorithm is unique as it works on the MPC Source SSA-form representation. We posit that vectorization over MPC Source is a new problem that warrants a new look, in part because of MPC’s unique linear structure and in part because vectorization meshes in with other MPC-specific optimizations in non-trivial ways (other works have explored manual vectorization and protocol mixing in an ad-hoc way, e.g., [?, ?, ?]).

§?? describes our dependence analysis and §?? describes scalar expansion, which lifts scalars (and arrays) to the corresponding loop dimensionality to create opportunities for vectorization. §?? describes our core vectorization algorithm and §?? argues correctness of the vectorization transformation. §?? extends vectorization with array writes.

5.1 Dependence Analysis

We build a dependence graph where the nodes are the MPC Source statements and the edges represent the def-use relations.

Def-use Edges. We distinguish the following def-use edges:

- same-level edge $X \rightarrow Y$ where X and Y are in the same loop nest, say i, j, k . E.g., the def-use edge 9 to 10 in the Biometric MPC Source in Listing ?? is a same-level edge. A same-level edge can be a back-edge in which case a ϕ node is the target of the edge. E.g., 15 to 4 in Biometric is a same-level back-edge.

- outer-to-inner $X \rightarrow Y$ where X is in an outer loop nest, say i , and Y is in an inner one, say i, j, k . E.g., 1 to 4 in Biometric forms is an outer-to-inner edge.
- inner-to-outer $X \rightarrow Y$ where X is a *phi*-node in an inner loop nest, i, j, k , and Y is in the enclosing loop nest i, j . E.g., the def-use from 8 to 12 gives rise to an inner-to-outer edge. An inner-to-outer edge can be a back-edge as well, in which case both X and Y are ϕ -nodes with the source X in a loop nested into Y ’s loop (not necessarily immediately).
- mixed forward edge $X \rightarrow Y$. X is in some loop i, j, k and Y is in a loop nested into i, j, k' . We transform mixed forward edges as follows. Let x be the variable defined at X . We add a variable and assignment $x' = x$ immediately after the i, j, k loop. Then we replace the use of x at Y with x' . This transforms a mixed forward edge into an “inner-to-outer” forward edge followed by an outer-to-inner forward edge. Thus, Basic Vectorization handles one of “same-level”, “inner-to-outer”, or “outer-to-inner” def-use edges.

Closures. We define $\text{closure}(n)$ where n is a PHI-node. Intuitively, it computes the set of nodes (i.e., statements) that form a dependence cycle with n . The closure of n is defined as follows:

- n is in $\text{closure}(n)$
- X is in $\text{closure}(n)$ if there is a same-level path from n to X , and $X \rightarrow n$ is a same-level back-edge.
- Y is in $\text{closure}(n)$ if there is a same-level path from n to Y and there is a same-level path from Y to some X in $\text{closure}(n)$.

5.2 Scalar Expansion

An important component of our algorithm is the scalar expansion to the corresponding loop dimensionality, which is necessary to expose opportunities for vectorization. In the Biometric example, $d = S[i*D+j] - C[j]$ equiv. to $d = S[i,j] - C[j]$, which gave rise to $N * D$ subtraction operations in the sequential schedule, is lifted. The argument arrays S and C are lifted and the scalar d is lifted: $d[i,j] = S[i,j] - C[i,j]$. The algorithm then detects that the statement can be vectorized.

Arrays. Conceptually, we treat all variables as arrays. There are three kinds of arrays.

- **Scalars:** These are scalar variables we expand into arrays for the purposes of vectorization. For those, all writes are canonical writes and all reads are canonical reads. We will *raise dimension* when a scalar gives rise to an outer-to-inner dependence edge (e.g., `sum!2` in line 6 of the MPC source code will be raised to a 1-dimensional array since `sum!2` is used in the inner j -loop). We will *drop dimension* when a scalar gives rise to an inner-to-outer dependence edge (e.g., `sum!2` for which the lifted inner loop computes D values, but the outer loop only needs the last one.)
- **Read-only input arrays:** There are no writes, while we may have non-canonical reads, $f(i, j, k)$. Vectorization

adds raise dimension operations at the beginning of the function to lift these arrays to the dimensionality of the loop where they are used, possibly *reshaping* the arrays. If there are multiple “views” of the input array, there would be multiple raise dimension statements to create each one of these views. The invariant is that at reads in loops, the reads of “views” of the original input array are canonical.

- Read-write output arrays: Writes are canonical (by restriction) but reads can be non-canonical. Dependences limit vectorization when non-canonical read access refers to array writes in previous iterations, thus creating loop-carried dependences. We may apply both raise and drop dimension, however, they respect the fixed dimensionality of the output array. The array cannot be raised to a dimension lower than its canonical (fixed) dimensionality and it cannot be dropped to lower dimension. In addition, non-canonical reads may require lifting (i.e., reshaping) of the array after the most recent write rather than in the beginning of the program in order to reduce a non-canonical read to a canonical one.

Raise dimension. The *raise_dim* function expands a scalar (or array). There are two conceptual versions of *raise_dim*. One reshapes an arbitrary access into a canonical read access in the corresponding loop. It takes the original array, the access pattern function $f(i, j, k)$ in loop nest i, j, k and the loop bounds $((i : I), (j : J), (k : K))$:

$$\text{raise_dim}(A, f(i, j, k), ((i : I), (j : J), (k : K)))$$

It produces a new 3-dimensional array A' by iterating over i, j, k and setting each element of A' as follows:

$$A'[i, j, k] = A[f(i, j, k)]$$

The end result is that uses of $A[f(i, j, k)]$ in loop nest i, j, k are replaced with canonical read-accesses to $A'[i, j, k]$ that can be vectorized. In the running Biometric example, $C' = \text{raise_dim}(C, j, (i : N, j : D))$ lifts the 1-dimensional array C into a 2-dimensional array. The i, j loop now accesses C' in the canonical way, $C'[i, j]$. Similarly, $S' = \text{raise_dim}(S, i * D + j, (i : N, j : D))$ tries to lift S , but the operation turns into a no-op because S is already a 2-dimensional array and the read access is canonical.

The other version of *raise_dim* lifts a lower-dimension array into a higher-dimension for access in a nested loop. It is necessary when processing outer-to-inner dependences. Here A is an i -array and raise dimension adds two additional dimensions:

$$\text{raise_dim}(A, (j : J, k : K))$$

This version is reduced to the above version by adding the access pattern function, which is just i :

$$\text{raise_dim}(A, i, (j : J, k : K))$$

Drop dimension. The corresponding *drop_dim* is carried out when an array written in an inner loop is used in an

enclosing loop. It takes a higher dimensional array, say i, j, k and removes trailing dimensions, say j, k :

$$\text{drop_dim}(A, (j : J, k : K))$$

It iterates over i and takes the result at the maximal index of j and k , i.e., the result at the last iterations of j and k :

$$A'[i] = A[i, J - 1, K - 1]$$

5.3 Basic Vectorization

We present our algorithm followed by an example on Biometric.

5.3.1 Algorithm

There are two key phases of the algorithm. Phase 1 inserts raise dimension and drop dimension operations according to def-uses. E.g., if there is an inner-to-outer dependence, it inserts *raise_dim*, and similarly, if there is an outer-to-inner dependence, it inserts *drop_dim*. After this phase operations work on arrays of the corresponding dimensionality and we optimistically vectorize all arrays.

Phase 2 proceeds from the inner-most towards the outer-most loop. For each loop it anchors dependence cycles (closures) around pseudo PHI nodes then removes vectorization from the dimension of that loop. There are two important points in this phase. First, it may break a loop into smaller loops which would discover opportunities for vectorization in intermediate statements in the loop. Second, it handles write arrays. It creates opportunities for vectorization in the presence of write arrays, even though Cytron’s SSA adds a back-edge to the array PHI-node, thus killing vectorization of statements that read and write that array.

The excerpts in red color in the pseudo code below highlight the extension with array writes. We advise the reader to omit the extension and assume just read-only arrays. We explain the extension in §?? details our algorithm. (As many of our benchmarks include array writes, it plays an important role.)

Phases 3 cleans up local arrays of references (this is an optional phase and our current implementation does not include it) and Phase 4 explicitly turns operations into MOTION SIMD operations.

{ Phase 1: Raise dimension of scalar variables to corresponding loop nest. We can traverse stmts linearly in MPC-source. }

for each MPC *stmt* : $x = Op(y_1, y_2)$ in loop i, j, k **do**

for each argument y_n **do**

 case def-use edge *stmt'* (def of y_n) \rightarrow *stmt* (def of x) of
 same-level: y'_n is y_n

 outer-to-inner: add $y'_n[i, j, k] = \text{raise_dim}(y_n)$ at *stmt'*

 (more precisely, right after *stmt'*)

 inner-to-outer: add $y'_n[i, j, k] = \text{drop_dim}(y_n)$ at *stmt*

 (more precisely, in loop of *stmt* right after loop of *stmt'*)

end for

{ Optimistically vectorize all. I means vectorized dimension. }


```

change to  $x[I, J, K] = Op(y'_1[I, J, K], y'_2[I, J, K])$ 
end for
{ Phase 2: Recreating for-loops for cycles; vectorizable
stmts hoisted up. }
for each dimension  $d$  from highest to 0 do
  for each PHI-node  $n$  in loop  $i_1, \dots, i_d$  do
    compute  $closure(n)$ 
  end for
  {  $cl_1$  and  $cl_2$  intersect if they have common statement
  or update same array; "intersect" definition can be ex-
  panded }
  while there are closure  $cl_1$  and  $cl_2$  that intersect do
    merge  $cl_1$  and  $cl_2$ 
  end while
  for each closure  $cl$  (after merge) do
    create for  $i_d$  in ... loop
    add PHI-nodes in  $cl$  to header block
    add target-less PHI-node for  $A$  if  $cl$  updates array  $A$ 
    add statements in  $cl$  to loop in some order of depen-
    dences
    { Dimension is not vectorizable: }
    change  $I_d$  to  $i_d$  in all statements in loop
    treat for-loop as monolith node for def-uses: e.g.,
    some def-use edges become same-level.
  end for
  for each target-less PHI-node  $A!1 = PHI(A!0, A!k)$  do
    in vectorizable stmts, replace use of  $A!1$  with  $A!0$ 
    discard PHI-node if not used in any  $cl$ , replacing  $A!1$ 
    with  $A!0$  or  $A!k$  appropriately
  end for
end for
{ Phase 3: Remove unnecessary dimensionality. }
{ A dimension  $i$  is dead on exit from stmt  $x[\dots i \dots] = \dots$  if
all def-uses with targets outside of the enclosing for  $i$  ...
MOTION loop end at target (use)  $x' = drop\_dim(x, i)$ . }
for each stmt and dimension  $x[\dots i \dots] = \dots$  do
  if  $i$  is a dead dimension on exit from stmt  $x[\dots i \dots] = \dots$ ,
  remove  $i$  from  $x$  (all defs and uses)
end for
{ Now clean up  $drop\_dim$  and  $raise\_dim$  }
for each  $x' = drop\_dim(x, i)$  do
  replace with  $x' = x$  if  $i$  is dead in  $x$ .
end for
do (1) (extended) constant propagation, (2) copy propaga-
tion and (3) dead code elimination to get rid of redundant
variables and raise and drop dimension statements
{ Phase 4: }
add SIMD for simdfied dimensions

```

5.3.2 Example: Biometric

We now demonstrate the workings of the basic algorithm on our running example. Recall the MPC Source for Biometric:

```

1 min_sum!1 = MAX_INT
2 min_idx!1 = 0
3 for i in range(0, N):
4   min_sum!2 = PHI(min_sum!1, min_sum!4)
5   min_idx!2 = PHI(min_idx!1, min_idx!4)

```

```

6 sum!2 = 0
7 for j in range(0, D):
8   sum!3 = PHI(sum!2, sum!4)
9   d = SUB(S[(i * D) + j], C[j])
10  p = MUL(d, d)
11  sum!4 = ADD(sum!3, p)
12  t = CMP(sum!3, min_sum!2)
13  min_sum!3 = sum!3
14  min_idx!3 = i
15  min_sum!4 = MUX(t, min_sum!3, min_sum!2)
16  min_idx!4 = MUX(t, min_idx!3, min_idx!2)
17 return (min_sum!2, min_idx!2)

```

Phase 1 of Vectorization Algorithm. The transformation preserves the dependence edges. It raises the dimensions of scalars and optimistically vectorizes all operations. The next phase discovers loop-carried dependences and removes affected vectorization.

In the code below statements (e.g., $min_sum!3 = sum!3$) are implicitly vectorized. The example illustrates the two different versions of $raise_dim$. E.g., $raise_dim(C, j, (i:N, j:D))$ reshapes the read-only input array. $drop_dim(sum!3)$ removes the j dimension of $sum!3$.

```

1 min_sum!1 = MAX_INT
2 min_sum!1^ = raise_dim(min_sum!1, (i:N))
3 min_idx!1 = 0
4 min_idx!1^ = raise_dim(min_idx!1, (i:N))
5 S^ = raise_dim(S, ((i * D) + j), (i:N, j:D))
6 C^ = raise_dim(C, j, (i:N, j:D))
7 for i in range(0, N):
8   min_sum!2 = PHI(min_sum!1^, min_sum!4)
9   min_idx!2 = PHI(min_idx!1^, min_idx!4)
10  sum!2 = 0 // Will lift, when hoisted
11  sum!2^ = raise_dim(sum!2, (j:D))
12  for j in range(0, D):
13    sum!3 = PHI(sum!2^, sum!4)
14    d = SUB(S^, C^)
15    p = MUL(d, d)
16    sum!4 = ADD(sum!3, p)
17    sum!3^ = drop_dim(sum!3)
18    t = CMP(sum!3^, min_sum!2)
19    min_sum!3 = sum!3^
20    min_idx!3 = i // Same-level, will lift when hoisted
21    min_sum!4 = MUX(t, min_sum!3, min_sum!2)
22    min_idx!4 = MUX(t, min_idx!3, min_idx!2)
23  min_sum!2^ = drop_dim(min_sum!2)
24  min_idx!2^ = drop_dim(min_idx!2)
25 return (min_sum!2^, min_idx!2^)

```

Phase 2 of Vectorization Algorithm. This phase analyzes statements from the innermost loop to the outermost. The key point is to discover loop-carried dependencies and re-introduce loops whenever dependencies make this necessary.

Starting at the inner phi-node $sum!3 = PHI(\dots)$, the algorithm first computes its closure. The closure amounts to the phi-node itself and the addition node $sum!4 = ADD(sum!3, p!3)$, accounting for the loop-carried dependency

of the computation of `sum`. The algorithm replaces this closure with a for-loop on j removing vectorization on j . Note that the SUB and MUL computations remain outside of the loop as they do not depend on PHI-nodes that are part of cycles. The dependences are from $p[l,j] = \text{MUL}(d[l,j], d[l,j])$ to the monolithic for-loop and from the for-loop to $\text{sum!3} \triangleq \text{drop_dim}(\text{sum!3})$. Lower case index, e.g., i , indicates non-vectorized dimension, while uppercase index, e.g., I indicates vectorized dimension.

After processing the inner loop code becomes:

```

1 min_sum!1 = MAX_INT
2 min_sum!1^ = raise_dim(min_sum!1, (i:N!0))
3 min_idx!1 = 0
4 min_idx!1^ = raise_dim(min_idx!1, (i:N))
5 S^ = raise_dim(S, ((i * D) + j), (i:N,j:D))
6 C^ = raise_dim(C, j, (i:N,j:D))
7 for i in range(0, N):
8   min_sum!2[I] = PHI(min_sum!1^[I], min_sum!4[I])
9   min_idx!2[I] = PHI(min_idx!1^[I], min_idx!4[I])
10  sum!2 = [0,...,0]
11  sum!2^ = raise_dim(sum!2, (j:D))
12  d[I,J] = SUB(S^[I,J], C^[I,J])
13  p[I,J] = MUL(d[I,J], d[I,J])
14  for j in range(0, D):
15    sum!3[I,j] = PHI(sum!2^[I,j], sum!4[I,j-1])
16    sum!4[I,j] = ADD(sum!3[I,j], p[I,j])
17    sum!3^ = drop_dim(sum!3)
18    t[I] = CMP(sum!3^[I], min_sum!2[I])
19    min_sum!3 = sum!3^
20    min_idx!3 = i
21    min_sum!4[I] = MUX(t[I], min_sum!3[I], min_sum!2[I])
22    min_idx!4[I] = MUX(t[I], min_idx!3[I], min_idx!2[I])
23  min_sum!2^ = drop_dim(min_sum!2)
24  min_idx!2^ = drop_dim(min_idx!2)
25 return (min_sum!2^, min_idx!2^)
```

When processing the outer loop two closures arise, one for $\text{min_sum!2}[I] = \text{PHI}(\dots)$ and one for $\text{min_idx!2}[I] = \text{PHI}(\dots)$. Since the two closures *do not* intersect, we have two distinct for-loops on i :

```

1 min_sum!1 = MAX_INT
2 min_sum!1^ = raise_dim(min_sum!1, (i:N))
3 min_idx!1 = 0
4 min_idx!1^ = raise_dim(min_idx!1, (i:N))
5 S^ = raise_dim(S, ((i * D) + j), (i:N,j:D))
6 C^ = raise_dim(C, j, (i:N,j:D))
7
8 sum!2 = [0,...,0]
9 sum!2^ = raise_dim(sum!2, (j:D))
10 d[I,J] = SUB(S^[I,J], C^[I,J])
11 p[I,J] = MUL(d[I,J], d[I,J])
12
13 for j in range(0, D):
14   sum!3[I,j] = PHI(sum!2^[I,j], sum!4[I,j-1])
15   sum!4[I,j] = ADD(sum!3[I,j], p[I,j])
16
17 sum!3^ = drop_dim(sum!3)
```

```

18 min_idx!3 = [0,1,2,...N-1] // i.e., min_idx!3 = [i, (i:N)]
19 min_sum!3 = sum!3^
20
21 for i in range(0, N):
22   min_sum!2[i] = PHI(min_sum!1^[i], min_sum!4[i-1])
23   t[i] = CMP(sum!3^[i], min_sum!2[i])
24   min_sum!4[i] = MUX(t[i], min_sum!3[i], min_sum!2[i])
25
26 for i in range(0, N):
27   min_idx!2[i] = PHI(min_idx!1^[i], min_idx!4[i-1])
28   min_idx!4[i] = MUX(t[i], min_idx!3[i], min_idx!2[i])
29
30 min_sum!2^ = drop_dim(min_sum!2)
31 min_idx!2^ = drop_dim(min_idx!2)
32 return (min_sum!2^, min_idx!2^)
```

Phase 3 of Vectorization Algorithm. This phase removes redundant dimensionality. It starts by removing redundant dimensions in MOTION loops followed by removal of redundant drop dimension statements. It then does (extended) constant propagation to "bypass" raise statements, followed by copy propagation and dead code elimination.

The code becomes closer to what we started with:

```

1 min_sum!1 = MAX_INT
2 min_idx!1 = 0
3 S^ = raise_dim(S, ((i * D) + j), (i:N,j:D))
4 C^ = raise_dim(C, j, (i:N,j:D))
5
6 sum!2 = [0,...,0]
7 d[I,J] = SUB(S^[I,J], C^[I,J])
8 p[I,J] = MUL(d[I,J], d[I,J])
9
10 // j is redundant for sum!3 and sum!4
11 for j in range(0, D):
12   sum!3[I] = PHI(sum!2[I], sum!4[I])
13   sum!4[I] = ADD(sum!3[I], p[I,j])
14
15 // drop_dim is redundant, removing
16 // then copy propagation and dead code elimination
17 min_idx!3 = [0,1,2,...N-1] // i.e., min_idx!3 = [i, (i:N)]
18
19 // i is redundant for min_sum!2, min_sum!4 but not for t[i]
20 for i in range(0, N):
21   min_sum!2 = PHI(min_sum!1, min_sum!4)
22   t[i] = CMP(sum!3[i], min_sum!2)
23   min_sum!4 = MUX(t[i], sum!3[i], min_sum!2)
24
25 // same, i is redundant for min_idx!2, min_idx!4
26 for i in range(0, N):
27   min_idx!2 = PHI(min_idx!1, min_idx!4)
28   min_idx!4 = MUX(t[i], min_idx!3[i], min_idx!2)
29
30 // drop_dim becomes redundant
31 return (min_sum!2, min_idx!2)
```

Phase 4 of Basic Vectorization. This phase adds SIMD operations:

```

1 min_sum!1 = MAX_INT
2 min_idx!1 = 0
3 S^ = raise_dim(S, ((i * D) + j), (i:N,j:D))
4 C^ = raise_dim(C, j, (i:N,j:D))
5
6 sum!2 = [0,...,0]
7 d[l,J] = SUB_SIMD(S^[l,J], C^[l,J])
8 p[l,J] = MUL_SIMD(d[l,J], d[l,J])
9
10 for j in range(0, D):
11     // l dim is a noop. sum is already a one-dimensional vector
12     sum!3[l] = PHI(sum!2[l], sum!4[l])
13     sum!4[l] = ADD_SIMD(sum!3[l], p[l,j])
14
15 min_idx!3 = [0,1,...N-1]
16
17 for i in range(0, N):
18     min_sum!2 = PHI(min_sum!1, min_sum!4)
19     t[i] = CMP(sum!3[i], min_sum!2)
20     min_sum!4 = MUX(t[i], sum!3[i], min_sum!2)
21
22 for i in range(0, N):
23     min_idx!2 = PHI(min_idx!1, min_idx!4)
24     min_idx!4 = MUX(t[i], min_idx!3[i], min_idx!2)
25
26 return (min_sum!2, min_idx!2)

```

5.4 Correctness Argument

We build a correctness argument that loosely follows Abstract Interpretation. First we define the MPC Source syntax. The domain of MPC Source programs expressible in the syntax (with certain semantic restrictions) is the abstract domain A . We then define the *linearization* of an MPC Source program as an interpretation over the syntax. The linearization, which is a *schedule* (as in §??), is the concrete domain C . Since we reason over def-use graphs in A we define a partial order relation over elements of A in terms of def-use relations. We define a partial order over elements of C as well, in terms of def-use relations in the concrete domain C . We prove two theorems that state (informally) that the schedule corresponding to the original program computes the same result as the schedule corresponding to the vectorized program.

MPC Source Syntax. Fig. ?? states the syntax and linearization semantics of MPC Source. Although notation is heavy, the linearization simply produces schedules as discussed in §??; the iterative MPC Source gives rise to what we called sequential schedule where loops are unrolled and MPC Source with vectorized dimensions gives rise to what we called parallel schedule. For simplicity, we consider only scalars and read-only arrays, however, the treatment extends to write arrays as well. $x[i, j, k]$ denotes the value of scalar variable x at loop nest i, j, k . Upper case J denotes a vectorized dimension and lower case i, k denote iterative dimensions. Our compiler imposes semantic restrictions over the syntax: (1) x is treated as a 3-dimensional array and (2) $x[i, j, k]$ must

be enclosed into for-loops on non-vectorized dimensions i and k :

```

1 for i in range(I):
2     ...
3     for k in range(K):
4         ... x[i,j,k] ...

```

Partial Orders. For each MPC Source program a we compute the def-use edges in the standard way: if statement $s1 \in a$ defines variable x , e.g., $x[i, j, k] = \dots$, and statement $s2 \in a$ uses x , e.g., $\dots = \dots x[i, j, k]$ and there is a path in CFG from $s1$ to $s2$, then there is a def-use edge from $s1$ to $s2$. We extend the dimensionality of a statement into $s1[i, j, k]$ where $s1[i, j, k]$ inherits the dimensionality of the left-hand-side of the assignment.

Let a_0, a_1 be two MPC Source programs in A . Two statements, $s \in a_0$ and $s' \in a_1$ are *same*, written $s \equiv s'$ if they are of the same operation and they operate on the same variables: same variable name and same dimensionality. Recall that dimensions in MPC Source are either iterative (lower case), or vectorized (upper case). Two statements are same even if one operates on an iterative dimension and the other one operates on a vectorized one, e.g., $s[i, j, k] \equiv s'[I, j, K]$. We extend the definition to def-use edges in the obvious way: a def-use edge $s_0 \rightarrow s_1$ in a_0 and an edge $s'_0 \rightarrow s'_1$ in a_1 are *same*, written $s_0 \rightarrow s_1 \equiv s'_0 \rightarrow s'_1$, if and only if $s_0 \equiv s'_0$, $s_1 \equiv s'_1$, and the two edges are both either forward or backward.

DEFINITION 1. Let $a_0, a_1 \in A$. We say that $a_0 \leq a_1$ iff for every def-use edge e in a_0 there is an edge e' in a_1 such that $e \equiv e'$.

The def-use edges in the concrete schedule are as expected: there is a def-use edge from statement $s1$ that defines $x[\underline{i}, \underline{j}, \underline{k}]$ to statement $s2$ that uses $x[\underline{i}, \underline{j}, \underline{k}]$ if $s1$ is scheduled ahead of $s2$ in the linear schedule. We note that the underlined indices, e.g., \underline{i} , refer to fixed values, not iterative or vectorized dimensions since in the concrete schedule all induction variables are expanded. E.g., there is a def-use edge from the statement that defines $x[0, 1, 2]$ and a statement that uses $x[0, 1, 2]$.

Theorems. The two theorems arising from the Basic vectorization optimization are as follows:

THEOREM 1. $a_0 \leq a_1 \Rightarrow \gamma(a_0) \subseteq \gamma(a_1)$.

THEOREM 2. Let a_0 be the iterative MPC Source and let a_1 be the vectorized MPC Source computed by Basic vectorization. We have that $a_0 \leq a_1$.

Theorem 1 states that a def-use edge in MPC Source a_0 gives rise to a set of def-use edges in $\gamma(a_0)$ and a “same” edge in a_1 gives rise to a set of def-use edges in $\gamma(a_1)$ and the former set is included in the latter one. This means that the computation of $\gamma(a_0)$ is carried out by $\gamma(a_1)$ as well, computing the same result. The theorem allows that a_1 and $\gamma(a_1)$ have larger state than a_0 and $\gamma(a_0)$, i.e., doing additional computation into additional memory locations. Theorem 2

s	$::= s_1; s_2$	$\gamma(s) = \gamma(s_1) ; \gamma(s_2)$	<i>sequence</i>
	$ x[i, J, k] = \text{op_SIMD}(y_1[i, J, k], y_2[i, J, k])$	$\gamma(x[i, J, k] = \text{op_SIMD}(y_1[i, J, k], y_2[i, J, k])) =$ $x[i, 0, k] = y_1[i, 0, k] \text{ op } y_2[i, 0, k] \parallel$ $x[i, 1, k] = y_1[i, 1, k] \text{ op } y_2[i, 1, k] \parallel \dots \parallel$ $x[i, J-1, k] = y_1[i, J-1, k] \text{ op } y_2[i, J-1, k]$	<i>operation</i>
	$ x[i, J, k] = \text{const}$	analogous	<i>constant</i>
	$ x[i, J, k] = \text{PHI}(x_1[i, J, k], x_2[i, J, k-1])$		<i>pseudo PHI</i>
	$ x[i, J, k] = \text{raise_dim}(x'[i], (J: J, k: K))$		<i>raise dimension(s)</i>
	$ x[i, J] = \text{drop_dim}(x'[i, J, k], k)$		<i>drop dimension(s)</i>
	$ \text{for } i \text{ in range}(I) : s$	$\gamma(\text{for } i \text{ in range}(I) : s) =$ $\gamma(s)[0/i] ; \gamma(s)[1/i] ; \dots ; \gamma(s)[I-1/i]$	<i>loop</i>

Figure 2: MPC Source Syntax and Semantics. γ defines the semantics of MPC source which is a linearization of MPC Source. A SIMD operation parallelizes operations across the vectorized J dimension. \parallel denotes parallel execution, which is standard. γ of a for loop unrolls the loop. $;$ denotes sequential execution. Iterative MPC Source trivially extends to non-vectorized dimensions over the enclosing loops.

establishes the correctness of vectorization — clearly, vectorization preserves all statements and def-use edges in the original MPC Source, and therefore the linearization computes the same result as the original MPC Source. (In this case we have an equivalence, $a_0 = a_1$ according to our partial order.)

5.5 Extension with Array Writes

5.5.1 Removal of Infeasible Edges

Array writes limit vectorization as they sometimes introduce infeasible loop-carried dependencies. Consider the classical example from [?]:

```

1 for i in range(N):
2   A[i] = B[i] + 10;
3   B[i] = A[i] * D[i-1];
4   C[i] = A[i] * D[i-1];
5   D[i] = B[i] * C[i];

```

In Cytron's SSA this code (roughly) translates into

```

1 for i in range(N):
2   A.1 = PHI(A.0, A.2)
3   B.1 = PHI(B.0, B.2)
4   C.1 = PHI(C.0, C.2)
5   D.1 = PHI(D.0, D.2)
6   A.2 = update(A.1, i, B.1[i] + 10);
7   B.2 = update(B.1, i, A.2[i] * D.1[i-1]);
8   C.2 = update(C.1, i, A.2[i] * D.1[i-1]);
9   D.2 = update(D.1, i, B.2[i] * C.2[i]);

```

There is a cycle around $B.1 = \text{PHI}(B.0, B.2)$ that includes statement $A.1 = \text{update}(A.0, i, B.1[i] + 10)$ and that statement won't be vectorized even though in fact there is no loop-carried dependency from the write of $B.1[i]$ at 7 to the read of $\dots = B.1[i]$ at 6.

The following algorithm removes certain infeasible loop-carried dependencies that are due to array writes. Consider a loop with index $0 \leq j < J$ nested at i, j, k . Here i represents the enclosing loops of j and k represents the enclosed loops in j .

for each array A written in loop j do
 { including enclosed loops in j }

```

dep = False
for each pair def:  $A_m[f(i, j, k)] = \dots$ , and use:  $\dots = A_n[f'(i, j, k)]$  in loop  $j$  do
  if  $\exists \underline{i}, \underline{j}, \underline{j}', \underline{k}, \underline{k'}$ , s.t.  $0 \leq \underline{i} < I$ ,  $0 \leq \underline{j}, \underline{j}' < J$ ,  $0 \leq \underline{k}, \underline{k}' < K$ ,  $\underline{j} < \underline{j}'$ , and  $f(\underline{i}, \underline{j}, \underline{k}) = f'(\underline{i}, \underline{j}', \underline{k}')$  then
    dep = True
  end if
end for
if dep == False then
  remove back edge into A's  $\phi$ -node in loop  $j$ .
end if
end for

```

Consider a loop j enclosed in some fixed i . Only if an update (definition) $A_m[f(i, j, k)] = \dots$ at some iteration \underline{j} references the *same* array element as a use $\dots = A_n[f'(i, j, k)]$ at some later iteration \underline{j}' , we may have a loop-carried dependence for A due to this def-use pair. (In contrast, Cytron's algorithm inserts a loop-carried dependency every time there is an array update.) The algorithm above examines all def-use pairs in loop j , including defs and uses in nested loops, searching for values $\underline{i}, \underline{j}, \underline{j}', \underline{k}, \underline{k'}$ that satisfy $f(\underline{i}, \underline{j}, \underline{k}) = f'(\underline{i}, \underline{j}', \underline{k}')$. If such values exist for some def-use pair, then there is a potential loop-carried dependence on A; otherwise there is not and we can remove the spurious backward edge thus “freeing up” statements for vectorization.

Consider the earlier example. There is a single loop, i . Clearly, there is no pair \underline{i} and \underline{i}' , where $\underline{i} < \underline{i}'$ that make $\underline{i} = \underline{i}'$ due to the def-use pairs of A 6-7 and 6-8. Therefore, we remove the back edge from 6 to the phi-node 2. Analogously, we remove the back edges from 7 to 3 and from 8 to 4. However, there are many values $\underline{i} < \underline{i}'$ that make $\underline{i} = \underline{i}' - 1$ and the back edge from 9 to 5 remains (def-use pairs for D). As a result of removing these spurious edges, Vectorization will find that statement 6 is vectorizable. Statements 7, 8 and 9 will correctly appear in the FOR loop.

Note however, that this step renders some array phi-nodes target-less. We handle target-less phi-nodes with a minor extension of Vectorization (Phase 2). First, we merge closures that update the same array. This simplifies handling of array ϕ -nodes: if each closure is turned into a separate loop each

loop will need to have its own array phi-node to account for the update and this would complicate the analysis. Second, we add the target-less node of array A back to the closure that updates A — the intuition is, even if there is no loop-carried dependence from writes to reads on A, A is written and the write (i.e., update) cannot be vectorized; therefore, the updated array has to carry to the next iteration of the loop. Third, in cases when the phi-node remains target-less, i.e., cases when the array write can be vectorized, we have to properly remove the phi-node replacing uses of the left-hand side of the phi-node with its arguments.

5.5.2 Restricting Array Writes

For now, we restrict array updates to *canonical updates*. Assume (for simplicity) a two-dimensional array $A[l,j]$. A canonical update is the following:

```

1 for i in range(I):
2   for j in range(J):
3     ...
4     A[i,j] = ...
5     ...

```

The update $A[i,j]$ can be nested into an inner loop and there may be multiple updates, i.e., writes to $A[i,j]$. However, update such as $A[i-1,j] = \dots$ or $A[i-1,j-1] = \dots$, etc., is not allowed. Additionally, while there could be several different loops that perform canonical updates, they must be of the same dimensionality, i.e., an update of higher or lower dimension, e.g., $A[i,j,k] = \dots$ is not allowed. We compute the *canonical dimensionality* of each write array by examining the array writes in the original program and rejecting programs that violate the canonical write restriction. This restriction simplifies reasoning in this early stage of the compiler; we will look to relax the restriction in future work.

Another restriction/assumption is that we assume the output array is given as input with initial values, and it is of size consistent with its canonical dimensionality.

Reads through an arbitrary formula, such as $A[i-1]$ for example, are allowed; currently, the projection function returns dummy values if the read formula is out of bounds; we assume the programmer ensures that the program still computes correct output in this case.

5.5.3 Changes to Basic Vectorization

In addition to the changes for the handling of target-less phi-nodes, Basic Vectorization has to handle def-use edges $X \rightarrow Y$ where X defines and Y uses an array variable. The definition can be an update $A.2 = \text{update}(A.1, i, \dots)$, a pseudo ϕ -node $A.2 = \text{PHI}(A.0, A.1)$, etc.. Note that ϕ -nodes for arrays have no subscript operations the way there are subscript operations in analysis-introduced arrays representing scalars. While there are variations, the most intuitive implementation will perform Basic Vectorization Phase 1 as is, inserting *raise_dim* and *drop_dim* in the same way. However, the implementation of raise dimension and drop dimension will be adapted because the dimension cannot be raised or dropped to a dimension lower than the canonical one. Consider a def-use edge $X \rightarrow Y$ for an array A.

- (1) same-level $X \rightarrow Y$. Do nothing, propagate the array, which happens to be of the right dimension.
- (2) inner-to-outer $X \rightarrow Y$ triggers the addition of *drop_dim*. However, the dimensionality cannot be dropped below the canonical dimensionality of the array. E.g., if the dimensionality of the loop enclosure X is already at the canonical one, then *drop_dim* has no effect.
- (3) outer-to-inner $X \rightarrow Y$ triggers *raise_dim*. Again, if the dimensionality of the loop enclosure of Y is smaller or same as the canonical dimensionality of the array, then it has no effect, otherwise, if dimensionality is greater than the canonical dimensionality, *raise_dim(...)* (at X) is the same as in Basic Vectorization.
- (4) "mixed" $X \rightarrow Y$. We assume that the mixed edge is transformed into an inner-to-outer followed by outer-to-inner edge before we perform vectorization, just as with Basic vectorization.

If the use of the array is a read $A[f(i, j, k)]$ different than a canonical read $A[i, j, k]$, then we need to add a reshape operation as all arrays are $A[i, j, k]$. It can be added after *raise_dim*/*drop_dim* or incorporated in these operations. The bulk of the change is in Phase 2 of Vectorization as outlined earlier.

5.5.4 Examples with Array Writes

Example 1. First, the canonical dimensionality of all A,B,C and D is 1. After Phase 1 of Vectorization the Aiken's array write example will be (roughly) as follows:

```

1 for i in range(N):
2   A.1 = PHI(A.0, A.2)
3   B.1 = PHI(B.0, B.2)
4   C.1 = PHI(C.0, C.2)
5   D.1 = PHI(D.0, D.2)
6   A.2 = update(A.1, i, B.1[i] + 10);
7   B.2 = update(B.1, i, A.2[i] * D.1[i-1]);
8   C.2 = update(C.1, i, A.2[i] * D.1[i-1]);
9   D.2 = update(D.1, i, B.2[i] * C.2[i]);

```

Note that since all def-uses are same-level (i.e., reads and writes of the array elements) no raise dimension or drop dimension happens.

Phase 2 computes the closure of 5; $cl = \{5, 7, 8, 9\}$ while 6 is vectorizable. Recall that 2,3, and 4 are target-less phi-nodes. Since the closure cl includes updates to B and C, the corresponding phi-nodes are added back to the closure and the def-use edges are added back to the target-less nodes. The uses of A.1 and B.1 in the vectorized statement turn into uses of A.0 and B.0 respectively; this is done for all original target-less phi-node. (But note that A.0 is irrelevant; the update writes into array A.2 in parallel.) Finally, the target-less phi-node for A is discarded.

```

1 A.2 = update(A.0, i, ADD_SIMD(B.0[i], 10));
2   equiv. to A.2[i] = ADD_SIMD(B.0[i], 10)
3 for i in range(N): // MOTION loop
4   B.1 = PHI(B.0, B.2)
5   C.1 = PHI(C.0, C.2)

```



```

6 D_1 = PHI(D_0, D_2)
7 B_2 = update(B_1, i, A_2[i] * D_1[i-1]);
8     equiv. to B_2 = B_1; B_2[i] = A_2[i] * D_1[i-1];
9 C_2 = update(C_1, i, A_2[i] * D_1[i-1]);
10 D_2 = update(D_1, i, B_2[i] * C_2[i]);

```

Example 2. Now consider the MPC Source of Histogram:

```

1 for i in range(0, num_bins):
2     res1 = PHI(res, res2)
3     for j in range(0, N):
4         res2 = PHI(res1, res3)
5         tmp1 = (A[j] == i)
6         tmp2 = (res2[i] + B[j])
7         tmp3 = MUX(tmp1, res2[i], tmp2)
8         res3 = Update(res2, i, tmp3)
9 return res1

```

The canonical dimensionality of `res` is 1. Also, the phi-node `res1 = PHI(res, res2)` is a target-less phi-node (the implication being that the inner for loop can be vectorized across i). After Phase 1, Vectorization produces the following code (statements are implicitly vectorized along i and j). In a vectorized update statement, we can ignore the incoming array, `res2` in this case. The update writes (in parallel) all locations of the 2-dimensional array, in this case it sets up each `res3[i,j] = tmp3[i,j]`.

```

1 A1 = raise_dim(A, j, ((i:num_bins),(j:N)))
2 B1 = raise_dim(B, j, ((i:num_bins),(j:N)))
3 l = raise_dim(i, ((i:num_bins),(j:N)))
4 for i in range(0, num_bins):
5     res1 = PHI(res, res2^)^ # target-less phi-node
6     res1^ = raise_dim(res1, (j:N))
7     for j in range(0, N):
8         res2 = PHI(res1^, res3)
9         tmp1 = (A1 == l)
10        tmp2 = (res2 + B1)
11        tmp3 = MUX(tmp1, res2, tmp2)
12        res3 = Update(res2, (l,j), tmp3)
13    res2^ = drop_dim(res2)
14    res1'' = drop_dim(res1)
15 return res1''

```

Processing the inner loop in Phase 2 vectorizes `tmp1 = (A1 == l)` along the j dimension but leaves the rest of the statements in a MOTION loop. Processing the outer loop is interesting. This is because the PHI node is a target-less node, and therefore, there are no closures! Several things happen. (1) Everything can be vectorized along the i dimension. (2) We remove the target-less PHI node, however, we must update uses of `res1` appropriately: the use at `raise_dim` goes to the first argument of the PHI function and the use at `drop_dim` goes to the second argument.

```

1 A1 = raise_dim(A, j, ((i:num_bins),(j:N)))
2 B1 = raise_dim(B, j, ((i:num_bins),(j:N)))
3 l1 = raise_dim(i, ((i:num_bins),(j:N)))
4
5 tmp1[l,j] = (A1[l,j] == l1[l,j])

```

```

6
7 res1^ = raise_dim(res, (j:N)) // replacing res1 with res, 1st arg
8 for j in range(0, N):
9     res2 = PHI(res1^, res3)
10    tmp2[l,j] = (res2[l,j] + B1[l,j])
11    tmp3[l,j] = MUX(tmp1[l,j], res2[l,j], tmp2[l,j])
12    res3 = Update(res2, (l,j), tmp3)
13    equiv. to res3 = res2; res3[l,j] = tmp3[l,j]
14    res2^ = drop_dim(res2)
15    res1 = drop_dim(res2^)^ // replacing with res2^, 2nd arg. NOOP
16 return res1

```

6 COMPILER BACK END

MOTION code generation requires that variables are marked as `plain` or `shared` following the type system in §???. We require that all inputs are marked as either shared or plain-text, however, we infer qualifiers for the rest of the variables. §??? briefly describes the taint analysis and §??? describes MOTION code generation.

6.1 Taint Analysis

The taint analysis works on MPC Source, which lacks if-then-else control flow. This significantly simplifies treatment as there is no need to handle conditionals and implicit flow. Specifically, the compiler uses the following rules, which are standard in positive-negative qualifier systems (here `shared` is the positive qualifier and `plain` is the negative one):

- (1) Loop counters and array bounds are always `plain`.
- (2) If any variable on the right-hand side `rhs` of an assignment is `shared`, then the assigned variable `lhs` is `shared` following subtyping rule `rhs <: lhs`.
- (3) Any variables that cannot be determined as `shared` via the above rules are `plain`.

The final rule is needed in examples like the following. In the below snippet `sum!2` and `sum!3` form a dependency cycle and there is no `shared` value that flows to either one. They are inferred as plaintext.

```

1 plaintext_array = [0, 1, 2, ...]
2 sum!1 = 0
3 for i in range(0, N):
4     sum!2 = PHI(sum!1, sum!3)
5     sum!3 = sum!2 + plaintext_array[i]

```

When converting to MOTION code, any plaintext value used in the right-hand side of a shared assignment is converted to a shared value for that expression.

6.2 From (Optimized) MPC Source to MOTION

MOTION supports FOR loops and SIMD operations, so translation from MPC source to MOTION C++ code is relatively straightforward.

Variable declarations: Our generated C++ uses the following variable-naming scheme: shared variables are named the same as in the MPC Source with the `!` replaced with an underscore (e.g. `sum!2` would be translated to `sum_2`). Plaintext

variables follow the same naming convention as shared variables but are prefixed with `_MPC_PLAINTEXT_`. The shared representation of constants are named `_MPC_CONSTANT_` followed by the literal constant (e.g. the shared constant 0 would be named `_MPC_CONSTANT_0`).

The generated MOTION code begins with the declaration of all variables used in the function, including loop counters. If a variable is a vectorized array, it is initialized to a correctly-sized array of empty MOTION shares. Additionally, each plaintext variable and parameter has a shared counterpart declared. Next, all constant values which are used as part of shared expressions are initialized as a shared input from party 0. Finally, plaintext parameters are converted used as shared inputs from party 0 to initialize their shared counterparts. *BEN: The note in parentheses is not true: we currently assume that all plaintext variables other than loop counters will be used in a shared expression. We initialize a shared version of them in the preamble (using the `_MPC_CONSTANT` variables or the plaintext parameter, depending on how the plaintext variable is initialized) and update that shared variable whenever the plaintext variable is updated. This is done to minimize the number of input gates (e.g. if a plaintext variable is upcast to shared in a loop, that would insert N input gates). With protocols that allow publicly known shared constants, this would not be necessary. This is described in the final subsection of this section.* *ANA: Got it, thanks! I think it is good now.*

Code generation: Once the function preamble is complete, the MPC Source is translated into C++ one statement at a time. The linear structure of MPC Source enables this approach to translation. If there is no vectorization present in a statement, translation to C++ is straightforward: outside of MUX statements and array updates, non-vectorized assignments, expressions, and returns directly translate into their C++ equivalents. Non-vectorized MUX statements are converted to MOTION’s MUX member function on the condition variable. Array updates are translated into two C++ assignments: one to update the value in the original array and one to assign the new array as shown in Listing ??.

MPC FOR loops are converted to C++ FOR loops which iterate the loop counter over the specified range. Pseudo PHI nodes are broken into two components: the “FALSE” branch which assigns the initial value of the PHI node and the “TRUE” branch which assigns the PHI node’s back-edge. The assignment of the “FALSE” branch occurs right before the PHI node’s enclosing loop. As these assignments may rely on the loop counter, the loop counter is initialized before these statements. Inside of the PHI node’s enclosing loop, a C++ `if` statement is inserted to only assign the true branch of the PHI node after the first iteration. Listing ?? illustrates this translation.

Vectorization and SIMD operations: Vectorization is handled with utility functions to manage accessing and updating slices of arrays. All SIMD values are stored in non-vectorized form as 1-dimensional `std::vectors` in row-major order. Whenever a SIMD value is used in an expression, the utility function

`vectorized_access()` takes the multi-dimensional representation of a SIMD value, along with the size of each dimension and the requested slice’s indices, and converts that slice to a MOTION SIMD value. Because MOTION supports SIMD operations using the same C++ operators as non-SIMD operations, we do not need to perform any other transformations to the expression. Therefore, once vectorized accesses are inserted the translation of an expression containing SIMD values is identical to that of expressions without SIMD values.

Similarly, the `vectorized_assign()` function assigns a (potentially SIMD) value to a slice of a vectorized array. This operation cannot be done with a simple subscript as SIMD assignments will update a range of values in the underlying array representation. *ANA: Changed non-vectorized j array representation. Check if correct.*

Updating SIMD arrays is also implemented differently from updating non-vectorized arrays. Instead of separating the array update from the assignment of the new array, these steps are combined with the `vectorized_update()` utility function. This function operates identically to `vectorized_assign()`, however it additionally returns the array after the assignment occurs. This value is then used for the assignment to the new variable. Listing ?? illustrates `vectorized_assign()` and `vectorized_update()` on the Biometric example.

BEN: The compiler and C++ internally uses “lift” as the terminology for `raise_dim()`, but the paper does not :(... ANA: True. To make matters worse, most of the explanation on this comes in the next section. But I’ll leave as is for now but leave the comments too because it needs work. *BEN: Attempted to explain the naming, please review.*

Reshaping and raising dimensions: Raising the dimensions of a scalar or array uses the `lift()` utility function which takes a lambda for the raised expression and the dimensions of the output. This function is also used for the scalar expansion of values which have been lifted out of FOR loops as described in §??. This function evaluates the expression for each permutation of indices along the dimensions and returns the resulting array in row-major order. The lambda accepts an array of integers representing the index along each of the dimensions being raised, and the translation of the expression which is being raised replaces each of the dimension index variables with the relevant subscript of this array. There is also a special case of the `lift()` function which occurs when we are raising an array. In this case, instead of concatenating the array for each index, *ANA: can we remove “instead of concatenating the array”* we extend the array along all dimensions being raised which are not present in the array already. For example, when raising an array with dimensions $N \times M$ to an array with dimensions $N \times M \times D$, the input array will simply be extended along the D dimension: $A'[n, m, d] = A[n, m]$ for every d . If the input array is already correctly sized it will be returned as-is.

Dropping dimensions use the `drop_dim()` and `drop_dim_monoreturn()` utility functions. They function identically but the latter returns a scalar for the case when the final dimension of an array is dropped. These functions

```
1 A[i] = val
```

IMP Source

```
1 A!2 = update(A!1, i, val)
```

MPC Source

```
1 A_1[i] = val;
2 A_2 = A_1;
```

MOTION Code

Table 2: MOTION Translation: Array Updates

```
1 for i in range(N):
2     tmp = PHI(arr[j], val!0)
3     ...
```

MPC Source

```
1 _MPC_PLAINTEXT_i = 0;
2 tmp = arr[_MPC_PLAINTEXT_i];
3 for (; _MPC_PLAINTEXT_i < _MPC_PLAINTEXT_N; _MPC_PLAINTEXT_i++) {
4     if (_MPC_PLAINTEXT_i != 0) {
5         tmp = val_0;
6     }
7     ...
8 }
```

MOTION Code

Table 3: MOTION Translation: FOR loop with Phi nodes

```
1 sum!4[i] = ADD.SIMD(sum!3[i], p[i, j])
```

MPC Source

```
1 vectorized_assign(sum_4, {_MPC_PLAINTEXT_N}, {true}, {},
2     vectorized_access(sum_3, {_MPC_PLAINTEXT_N}, {true}, {}) +
3     vectorized_access(p, {_MPC_PLAINTEXT_N, _MPC_PLAINTEXT_D}, {true, false},
4     {_MPC_PLAINTEXT_j}));
```

MOTION Code

Table 4: MOTION Translation: Assignment to SIMD value

```
1 raise_dim(i + j, (i:N, j:M))
```

MPC Source

```
1 lift(std::function([&](const std::vector<std::uint32_t > &idxs) {return idxs[0] + idxs[1];}),
2     {_MPC_PLAINTEXT_N, _MPX_PLAINTEXT_M})
```

MOTION Code

Table 5: MOTION Translation: Raising dimensions

take the non-vectorized representation of an array, along with the dimensions of that array, and return the array with the final dimension dropped.

Upcasting from plaintext to shared: Currently, our compiler only supports the **Bmr** and **BooleanGMW** protocols as MOTION does not implement all operations for other protocols. MOTION does not support publicly-known constants for these protocols, so all conversions from plaintext values to shares are performed by providing the plaintext value as a shared input from party 0. Due to this limitation, our translation to MOTION code attempts to minimize the number of conversions from a plaintext value. This is accomplished by creating a shared copy of each plaintext variable and updating that copy in lock-step with the plaintext variable. Since variables are often initialized to a common constant value (e.g. 0), this approach decreases the number of input gates by only creating a shared input for each initialization constant. Loop counters must still be converted to a shared value on each iteration that they are used, however we only generate this conversion when necessary, i.e., when the counter flows to a

shared computation. This is to prevent unnecessary increase in the number of input gates when loop counters are only used as plaintext. *BEN: Ishaq or Vassilis: please check over this paragraph... I don't want to make some mistake about MOTION's capabilities.*

Due to the SSA translation phase as well as the conversions to and from SIMD values which our utility functions perform, our generated vectorized MOTION code often includes multiple copies of arrays and scalar values. These copies do not incur a runtime cost as the arrays simply hold *pointers* to the underlying shares, so no new shares or gates are created as a result of this copying. Cost in MPC programs is dominated by shares and computation on shares.

7 EXPERIMENTAL RESULTS

8 RELATED WORK

MPC languages and compilers. Languages and compilers for secure computation have seen significant attention and advances in recent years. The early MPC compilers Fairplay [?], and Sharemind [?] were followed by PICCO [?], Obliv-C [?],

TinyGarble [?], Wystiria [?], and others. A new generation of MPC compilers includes SPDZ/SCALE-MAMBA/MP-SPDZ [?] and the ABY/HyCC/MOTION [?, ?, ?] frameworks. These two families are the state-of-the art and are actively developed. Another recent development is Viaduct, a functional language and compiler that supports a range of secure computation frameworks, including MPC and ZKP. Hastings et al. present a review of compiler frameworks [?].

While each of these languages and compilers brings in new ideas and advances, none addresses the problem of “circuit independent” intermediate representation and optimization. We envision a classical compiler structure: (1) a Wysteria, Viaduct, Obliv-C, or IMP Source front end, including rich type systems and AST-level semantic analysis, compile into the MPC Source IR, (2) MPC Source-level optimizations take place, followed by (3) back-end compilers into circuits. Our focus is at the intermediate level.

Many works focus on the implementation of MPC protocols exposing an API to the programmer. For example, the ABY/MOTION line of compiler frameworks provides a library of MPC primitives; the programmer writes MPC programs in C++ on top of the library. These back ends implement different protocols and allow for mixing, but notably, they leave it to the programmer to assign different protocols to different parts of the computation and perform share conversion accordingly. In addition, MOTION provides SIMD primitives, which allows for efficient execution of MPC operations, but again, using SIMD primitives is the responsibility of the programmer. There is interest in frameworks for automatic mixing, e.g., [?, ?, ?].

Other works, e.g., Obliv-C [?], Wystiria [?] and Viaduct [?] focus on higher-level language design, particularly information-flow systems that restrict flow between secure and insecure parts of the program.

Classical HPC compilers. Automatic vectorization is a longstanding problem in high-performance computing (HPC). There are thousands of works in this area reflecting over 40 years of research. We presented a vectorization algorithm for MPC Source, essentially extending classical loop vectorization [?]. In HPC vectorization, conditional control flow presents a challenge — one cannot estimate the cost of a schedule or vectorize branches in a straightforward manner — in contrast to MPC Source vectorization. We view Karrenberg’s work on Whole function vectorization [?] as most closely related to ours — it linearizes the program and vectorizes both branches of a conditional applying masking to avoid execution of the branch-not-taken code, and selection (similar to MUX) to select the correct value based on the result of the condition at runtime. The problem is that masking and selection, or more generally, handling control predicates [?, ?], can lead to *slowdown*.

We argue that vectorization over linear MPC Source is a different problem, one that warrants a new look, while drawing from results in HPC. Since both branches of the conditional and the multiplexer *always* execute, not only can

we apply aggressive vectorization on linear code, but (perhaps more importantly) we can also build analytical models that accurately predict execution time. These models in turn would drive optimizations such as vectorization, protocol mixing, and others. Vectorization meshes in with those additional optimizations in non-trivial ways.

Furthermore, extensions of classical loop vectorization with array writes, arbitrary indexing, including non-affine indexing, and interaction with SSA are non-trivial and present novel challenges and opportunities for contribution. Polyhedral parallelization [?] considers a higher-level source (typically AST) representation, while our work takes advantage of linear MPC Source and SSA form. The work by Karrenberg [?] is rare in that space, in the sense that it considers vectorization over SSA form, which has similarities to MPC Source. We consider different array representation, notion of dependence, and reasoning about dependence, which we conjecture is more suitable for MPC Source. Buscher [?] considers SIMD-vectorization at the level of source code, which then combines with circuit-level optimizations in the TinyGarble compiler. He proposes using an off-the-shelf polyhedral compiler, however, application is limited to only two routines, essentially just inner product and euclidian distance; it is unclear how effective the off-the-shelf compiler is. In contrast, we consider vectorization at the level of MPC Source separating “backend-independent” vectorization and circuit-level amortization (done by MOTION). We apply our compiler on a wide range of routines.

9 CONCLUSION AND FUTURE WORK