Reverse-Mode AD of Multi-Reduce and Scan in Futhark

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ABSTRACT

We present and evaluate the Futhark implementation of reverse-mode automatic differentiation (AD) for the basic blocks of parallel programming: reduce, prefix sum (scan), and reduce by index (multi-reduce). We first present derivations of general-case algorithms, and then discuss several specializations that result in efficient differentiation of most cases of practical interest. We report an experiment that evaluates the performance of the differentiated code in the context of GPU execution, and highlights the impact of the proposed specializations as well as the strengths and weaknesses of differentiating at high level *vs.* low level (i.e., "differentiating the memory").

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1 INTRODUCTION

Nowadays, most domains have embraced machine learning (ML) methods, which fundamentally rely on gradients to learn. But even in the absence of ML, the computation of gradients is essential in many compute-hungry applications ranging over various domains, such as financial risk analysis of large portfolios utilizing complex pricing methods [15, 37, 53], retrieval (and tuning) of parameters and associated uncertainties from satellite products in remote sensing [12, 29, 46], solving non-linear inverse problems or for sensitivity analysis of large numerical simulations in physics [28, 49].

Automating the computation of derivatives — known as automatic differentiation (AD) — has been a central contributor to facilitating advancements in such domains, for example in designing and training new ML models [3]. As such, an argument can be made that AD should be a first-class citizen in high-level parallel languages [22, 43]. This requires algorithms that offer reliable and efficient differentiation of (unrestricted) parallel programs that scales well on modern, highly parallel hardware, such as GPUs.

A feasible way of achieving this is to differentiate at a "high level", by building the AD algorithm around higher-order array combinators — common to functional programming — whose richer semantics allows to lift the level of abstraction at which the compiler reasons. The first step in this endeavor is to develop efficient rules for differentiating such parallel combinators.

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This paper presents and evaluates algorithms for reverse-mode differentiation of reduce, reduce-by-index and scan, which are implemented in (but not restricted to the context of) the Futhark language [21]. For each combinator, we present a "general-case" algorithm that typically re-writes the differentiation of the combinator in terms of a less efficient combinator. For example, reduce requires prefix sum (scan), reduce-by-index require multi-scan, and scan's differentiation is not AD efficient. (The algorithms for reduce and reduce-by-index are AD efficient, but have largish constants).

These inefficiencies motivate the development of a set of specializations that significantly reduce the AD overheads of most cases of practical interest. Specializations include:

- addition, min, max and multiplication — these are known and are not claimed as contributions, but are treated here for completeness,
- vectorized operators, which are reduced to scalar operators by re-write rules that interchange the encompassing reduce(-by-index) or scan with the vectorizing map,
- invertible commutative operators that, for example, allow the differentiation of reduce(-by-index) to be written in terms of a reduce(-by-index) with an extended operator, rather than in terms of (multi-)scans,
- simple sparsity (compiler) optimizations that exploit the block-diagonal structure of Jacobians and, for example, allow differentiating a scan with 5×5 matrix multiplication operator at a reasonable $4.1\times$ AD overhead.

Note that the differentiation of reduce has been (briefly) covered in [50] and is not a contribution of this paper; we still recount it in detail for completeness and because the rationale behind it drives the treatment of the other operators.

Most important, we report an experiment that evaluates the practical GPU performance of the reverse-mode differentiation of reduce, scan and reduce by index on various operators. Comparisons are made with the algorithms of the closest-related approach [44], which we have implemented in Futhark. The evaluation demonstrates significant performance gains, and that most operators can be differentiated on GPU quite efficiently, while very few of them (e.g., reduce-by-index with saturated addition) appear better suited to lower-level approaches that "differentiate the memory".

In summary, key contributions of this paper are:

1 "general-case" reverse-mode AD algorithms for reduce-by-index and scan, the former of which is AD efficient,
2 a set of specializations that offer practical efficiency for most cases of interest,
3 to our knowledge, the first evaluation of the GPU performance of reverse-mode AD for reduce(-by-index) and scan;

```
1 P($x_0$, $x_1$):
2   $t_0$ = sin($x_0$)
3   $t_1$ = $x_1$ · $t_0$
4   $y$ = $x_0$ + $t_1$
5   return $y$
```

```
1  P'($x_0$, $x_1$):
2    $t_0$ = sin($x_0$)
3    $t_1$ = $x_1$ · $t_0$
4    $y$ = $x_0$ + $t_1$
5    $\overline{y}$ = 1
6    $\overline{x_0}$ = 0, $\overline{t_1}$ = 0
7    $\overline{x_0}$ += 1 · $\overline{y}$    -- $\frac{\partial(x_0+t_1)}{\partial x_0} \equiv 1$
8    $\overline{t_1}$ += 1 · $\overline{y}$    -- $\frac{\partial(x_0+t_1)}{\partial t_1} \equiv 1$
9    $\overline{x_1}$ = 0, $\overline{t_0}$ = 0
10   $\overline{x_1}$ += $t_0$ · $\overline{t_1}$    -- $\frac{\partial(x_1 \cdot t_0)}{\partial x_1} \equiv t_0$
11   $\overline{t_0}$ += $x_1$ · $\overline{t_1}$    -- $\frac{\partial(x_1 \cdot t_0)}{\partial t_0} \equiv x_1$
12   $\overline{x_0}$ += cos($x_0$) · $\overline{t_0}$
13                                -- $\frac{\partial \sin(x_0)}{\partial x_0} \equiv \cos(x_0)$
14   return ($\overline{x_0}$, $\overline{x_1}$)
```

Figure 1: Simple example demonstrating reverse-mode differentiation of straight-line scalar code.

the evaluation demonstrates the claims and the impact of the proposed specializations and highlights the strengths and weaknesses of the approach of differentiating at a high level.

2 PRELIMINARIES

This section provides a brief overview of the functional language used to discuss the differentiation algorithms and a brief introduction to reverse-mode automatic differentiation (AD), which are hopefully sufficient to understand the rest of the paper.

2.1 Brief Overview of the Futhark Language

Futhark is a purely-functional parallel-array language that borrows its syntax from a combination of Haskell and ML, and in which parallelism is explicitly expressed by means of a nested composition of standard second-order array combinators (SOAC), such as map, reduce, scan, and scatter (parallel write). Scatter has type:

$$\textbf{scatter} : \forall n, m, \alpha.\ *[n]\alpha \rightarrow [m]\textbf{i64} \rightarrow [m]\alpha \rightarrow *[n]\alpha$$

where **i64** denotes the 64-bits integral type, $[n]\alpha$ denotes a size-typed [16] array of length n, and $*[n]\alpha$ denotes a unique type, e.g., when used as an argument it means that the corresponding array is consumed by the scatter operation, and when used for the result it means that it does not alias any of the non-unique arguments.

Semantically, scatter "updates in place" the first array argument at the indices specified in the second array with the corresponding values stored in the third argument. Scatter has work $O(m)$ and depth $O(1)$. The other combinators are standard.

For brevity, the notation used in this paper is informal and omits universal quantification and types, whenever they are easily inferable by the reader.

2.2 Brief Introduction to Reverse-Mode AD

The first-order partial derivatives of a differentiable function $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ forms an $m \times n$ Jacobian matrix:

$$\mathrm{J} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

Reverse mode AD computes a row of the Jacobian at a time. (In contrast, forward mode AD computes a column of the Jacobian at at time. Reverse mode AD is thus preferred when the size of the result is much smaller than the input size.)

For a program $P(\ldots, x_i, \ldots) = y \in \mathbb{R}$, reverse-mode AD computes the *adjoint* of each (intermediate) program variable t, denoted $\overline{t} = \frac{\partial y}{\partial t}$, that captures the sensitivity of the result to changes in t.

The *primal trace* (original program) is first executed to save intermediate program values on a *tape* (abstraction). The tape is subsequently used by the *return sweep*, which computes the *adjoint* of each variable in reverse program order.

Initially $\overline{y} = \frac{\partial y}{\partial y} = 1$, and eventually the adjoints of the input $\overline{x_i} = \frac{\partial y}{\partial x_i}$ are computed by applying the core re-write rule:

$$v = f(a, b, \ldots) \implies \begin{array}{l} v = f(a,b,\ldots) \\ \quad\vdots \\ \overline{a} \mathrel{+}= \dfrac{\partial f(a,b,\ldots)}{\partial a}\overline{v} \\ \overline{b} \mathrel{+}= \dfrac{\partial f(a,b,\ldots)}{\partial b}\overline{v} \\ \quad\ldots \end{array} \tag{1}$$

where the vertical dots correspond to the statements of the primal trace and their differentiation (on the return sweep). In particular, the vertical dots compute the final value of $\overline{v}$ – because v cannot possibly be used before its definition — and partial values for $\overline{a}$ and $\overline{b}$, i.e., corresponding to their uses after the statement $v = f(a, b, \ldots)$ in the original program.

Figure 1 demonstrates how reverse-mode AD is applied to a simple example consisting of straight-line scalar code. The left-hand side shows the original program. The right-hand side shows the differentiated code:

lines 2-4: the primal trace is re-executed to bring into scope the values of t_0 and t_1 which are used in differentiation;
line 5: the adjoint of the result is initialized to $\frac{\partial y}{\partial y} = 1$;
lines 6-8 correspond to differentiating the last statement of the original program (line 4) by the application of re-write rule 1. Note that adjoints are initialized before their first use.
lines 9-11 and 12-13 similarly correspond to the differentiation of statements at lines 3 and 2 in the original program.

Reverse-mode AD is exposed to the user by means of the classical *vector-Jacobian product* (**vjp**) interface:

$$\textbf{vjp} : (f : \alpha \rightarrow \beta) \rightarrow (x : \alpha) \rightarrow (\overline{y} : \beta) \rightarrow \alpha$$

vjp is a second-order function that computes the derivative of f at point x given that the adjoint of the result is $\overline{y}$. For example, the Jacobian of f at point x can be computed by mapping `vjp f x` on the unit vectors of the result type β, i.e., each invocation of **vjp**

computes one row of the Jacobian. The notation in 1 is a bit confusing: since **vjp** computes the vector-Jacobian product, it should probably be written as $\overline{a}$ += $\overline{v}\ \frac{\partial f(a,b,\ldots)}{\partial a}$, as it makes a difference when v is a vector. We warn the reader that the rest of the paper will use the established, albeit slightly confusing, notation.

In the paper, we will denote by $\mathbb{VJP}$ the program transformation (hinted in figure 1) that implements reverse-mode AD and we will use $\mathbb{VJP}^{\mathbb{LAM}}$ to denote the code transformation applied to the syntactic category of lambda functions. (Other syntactic categories are, for example expressions, statements and body of statements).

3 PRELIMINARIES: REVERSE-AD OF REDUCE

This section presents the algorithm (re-write rules) that implements reverse-mode differentiation of **reduce**: Section 3.1 presents the "general" case, in which the reduce operator is merely constrained to not use any free variables, Section 3.2 specializes the algorithm to commonly-used operators addition, min/max, multiplication and to vectorized operators, and Section 3.3 specializes the algorithm to a class of operators that are commutative and invertible.

The goal of this section is to make the presentation self-contained, since the rest of the paper builds on the type of reasoning used for reduce. The content of this section is not a scientific contribution of this paper because, for example, the general rule and specialized cases were briefly presented elsewhere [50] and the specialization proposed in Section 3.3 is not implemented yet.

3.1 General Algorithm

We start deriving the general rule from the definition of **reduce**. Given an associative operator $\odot$ with neutral element $e_\odot$, we have

$$y = \textbf{reduce}\ \odot\ e_\odot\ [a_0, a_1, \ldots, a_{n-1}]$$

which is equivalent to

$$y = a_0 \odot a_1 \odot \ldots \odot a_i \odot \ldots \odot a_{n-1}$$

For each a_i, we can then group the terms of the reduce as:

$$y\ =\ \underbrace{a_0\ \odot \cdots \odot\ a_{i-1}}_{l_i}\ \odot a_i\ \odot\ \underbrace{a_{i+1}\ \odot \cdots \odot\ a_{n-1}}_{r_i}$$

Assuming l_i and r_i are known (i.e., already computed) and that $\odot$ does not use any free variable then we can directly apply the core rule for reverse AD, given in equation 1, to compute all the contributions to the adjoints $\overline{a_i}$ in parallel:

$$\overline{a_i}\ \mp= \frac{\partial(l_i \odot a_i \odot r_i)}{\partial a_i}\ \overline{y} \qquad (2)$$

where $\overline{y}$ — the adjoint of the reduction result y — has aleardy been determined by execution of the return sweep until this point.

Here, l_i and r_i for all $i = 0, \ldots, n-1$ can be computed by two exclusive scans; one on the original array and one on the reversed array. Exclusive scan is defined as:

$$\textbf{scan}^{exc} \odot e_\odot\ [a_0, a_1, \ldots, a_{n-1}]\ \equiv\ [e_\odot,\ a_0,\ a_0{\odot}a_1, \ldots, a_0{\odot}\ldots a_{n-2}]$$

Figure 2 shows the general-case algorithm for reduction, where

- $\triangleright$ is the *pipe operator* which composes functions left to right,
- $\mp$ is a multidimensional addition (implemented as a tower of **map**s) with rank equal to the rank of the input array, and

```
-- Assuming array as of length n
-- Primal trace is the same as original:
let y = reduce ⊙ $e_\odot$ as

-- Return sweep:
let ls = scan$^{exc}$ ⊙ $e_\odot$ as   -- forward exclusive scan
let rs = reverse ad          -- reverse exclusive scan
         ▹ scan$^{exc}$ ($\lambda x\ y \to y\ \odot\ x$) $e_\odot$
         ▹ reverse
    -- applying the core rule of reverse AD:
let $\overline{as}$ ∓= map3 ($\lambda\ l_i\ a_i\ r_i \to \overline{f_{l_i,r_i}}\ a_i$) ls as rs
    denoting $\overline{f_{l_i,r_i}}$ ← $\mathbb{VJP}^{\mathbb{LAM}}$ ($\lambda a_i \to l_i \odot a_i \odot r_i$) $\overline{y}$
```

Figure 2: Reverse AD general re-write rule for reduce

- $\overline{f_{l_i,r_i}}$ is recursively obtained by applying the $\mathbb{VJP}^{\mathbb{LAM}}$ transform to generate code corresponding to $\partial(l_i{\odot}a_i{\odot}r_i)/\partial a_i \cdot \overline{y}$.

We observe that the transformation preserves the parallel asymptotic of the original program — since both **reduce** and **scan** have linear work and logarithmic depth. However, it incurs a rather large AD overhead since, even under aggressive fusion, the differentiated code still requires about 8× more global-memory accesses than the original reduce. Fortunately, standard operators, discussed next, admit more efficient differentiation.

3.2 Specialization for Common Operators

Specialized rules for addition, min, max and multiplication on numeric types are known [23] — the rule of multiplication in [23] uses two **scan**s, but a more efficient one is presented in [50]. This section recounts them in more detail for completeness.

3.2.1 Addition. The primal trace of `let y = reduce (+) 0 as` is the same as the original and its return sweep adds $\overline{y}$ to each element of $\overline{as}$ since $\partial(l_i{+}a_i{+}r_i)/\partial a_i$ simplifies to 1, hence the return sweep is:

$$\texttt{let}\ \overline{as} = \texttt{replicate}\ n\ \overline{y}\ \ \triangleright\ \ \texttt{map2}\ (+)\ \overline{as}$$

We expect the AD overhead to be as high as 2× since the original code performs n reads from global memory, and the differentiated code performs $2 \cdot n$ accesses: n reads and n writes.[1]

3.2.2 Min/Max. A reduction with min (max) selects the minimum (maximum) element of an array. Assume that the latter is located at position k. It follows that the contribution to the adjoint of a_i is:

- 0 for any $i \neq k$ because the result y does not depend on a_i,
- $\overline{y}$ for the k^{th} element, since $\frac{\partial min(a_0,\ldots,a_k,\ldots,a_{n-1})}{\partial a_k} = \frac{\partial a_k}{\partial a_k} = 1$.

The primal trace is thus a lifted reduction whose associative and *commutative* operator, denoted $\texttt{min}^L$, keeps track of the minimum value together with its index — in case of duplicates we choose the smallest index corresponding to the minimum value:

$$\texttt{let}\ (k, y) = \texttt{zip}\ [0, \ldots, \texttt{n}-1]\ \texttt{as}\ \triangleright\ \texttt{reduce}\ \texttt{min}^L\ (\texttt{n},\ \infty)$$

The return sweep updates (only) the adjoint at position k:

$$\begin{aligned}&\texttt{let}\ \overline{a_{min}} = \texttt{if}\ k < n\ \texttt{then}\ \overline{as}[k] + \overline{y}\ \texttt{else}\ 0_\alpha\\ &\texttt{let}\ \overline{as} = \texttt{scatter}\ \overline{as}\ [\ \texttt{k}\ ]\ [\ \overline{a_{min}}\ ]\end{aligned}$$

[1]The reduce of the primal performs n reads, and the map of the return sweep performs n reads and n writes: The replicate is fused with the map and thus is not considered.

```
-- Original:
let y = reduce (*) 1 as

-- Primal trace:
let (n^{=0}, y^{>0}) =
  as ▷ map (λa → if a==0 then (1i64,1) else (0,a))
     ▷ reduce (+, *) (0i64, 1)
let y = if n^{=0} > 0 then 0 else y^{>0}

-- Return sweep:
let a̅s̅ = map2 (λ a a̅ →
                  a̅ + if n^{=0} == 0
                      then (y / a) * y̅
                      else if n^{=0} == 1 && a == 0
                           then y^{>0} * y̅
                           else 0
               ) as a̅s̅
```

Figure 3: Reverse AD rule for reduce with multiplication

The update is implemented in terms of the parallel-write operator **scatter**, which has the semantics that it discards the updates of out of bounds indices (e.g., the case when as is empty).

We expect the AD overhead to be around 2×: because the original and primal both perform n memory reads to compute the reduction — the index space $[0, \ldots, n-1]$ is fused, hence not manifested in memory — and the return sweep might need to initialize $\overline{as}$ (with zeroes), which requires another n memory writes. GPU implementations may suffer from (expensive) host-to-device transfers if scalars and arrays are kept in the CPU and GPU memory space, respectively, i.e., the values of k and $\overline{as}[k]$ have to be brought from GPU to CPU, and the value of $\overline{a_{min}}$ has to be transferred back to GPU.

3.2.3 *Multiplication.*

The quantity of interest is

$$\frac{\partial y}{\partial a_i} = \frac{\partial(l_i \cdot a_i \cdot r_i)}{\partial a_i} = l_i \cdot r_i$$

If all elements would be known to be different than zero, then $l_i \cdot r_i$ can be computed as y/a_i, resulting in the return sweep:

$$\textbf{let } \overline{as} \mathrel{+}= \textbf{map } (\lambda\ a_i \ \rightarrow\ (y/a_i)\ *\ \overline{y})\ as$$

The case when some elements may be zero is treated by extending the primal to compute (i) the number of zero elements $n^{=0}$ and (ii) the product of the non-zero elements $y^{>0}$. Two additional cases require consideration:

- If exactly one element at index i_0 is zero, then $l_i * r_i$ is zero for all other elements and only $\overline{a_{i_0}}$ is updated: $\overline{a_{i_0}} \mathrel{+}= y^{>0} * \overline{y}$.
- If more than one zero exists, then $\overline{as}$ remains unchanged.

Figure 3 shows the code that implements this algorithm. The reason for moving the **if** inside the **map** is to permit utilization of outer(-map) parallelism, in case it exists (otherwise the introduced control flow might prevent it). Assuming that in the common case as does not contain zeroes, the AD overhead can be as high as:

3× if $\overline{as}$ is initialized at this point (i.e., lastly used in the original reduce), because its initialization will be fused with the **map**,

4× otherwise, i.e., $2 \cdot n$ reads and n writes due the **map** on the return sweep and n reads due to the **reduce** of the primal.

3.2.4 *Vectorized Operators.*

Vectorized operators are transformed with Irwim re-write rule [19] that essentially interchanges the outer reduce inside the inner map, thus simplifying the reduce operator:

$$\begin{array}{c} \textbf{reduce}\ (\textbf{map2}\ \odot)\ (\textbf{replicate}\ \mathrm{n}\ e_\odot)\ \mathrm{matrix} \\ \equiv \\ \textbf{map}\ (\textbf{reduce}\ \odot\ e_\odot)\ (\textbf{transpose}\ \mathrm{matrix}) \end{array} \qquad (3)$$

The intuition is that summing up the elements on each column of a matrix (**reduce (map2 (+))**) is equivalent to transposing the matrix, and summing up the elements on each row (**map (reduce (+))**). This is generalized to arrays of arbitrary rank by extending **transpose** to permute the two outermost dimensions.

The Irwim rule is systematically applied in the $\mathbb{VJP}$ transformation whenever it matches and differentiation is performed on the *resulting code*. This is practically important because:

- it enables efficient differentiation of vectorized common operators without extra implementation effort;
- some differentiation rules [44] do not turn reductions with vectorized operators into scans or reductions with vectorized operators — and such (arbitrary) operators on arrays are challenging to be mapped efficiently to the GPU hardware, e.g., the code produced by Futhark has abysmal performance.

3.3 Specialization for Invertible Operators

The treatment of multiplication hints that the underlying reasoning can be extended to encompass a larger class of operators. The key properties that we have used are

commutativity: in that $l_i \cdot a_i \cdot r_i$ can be rewritten as $l_i \cdot r_i \cdot a_i$,
invertibility: in that knowing the current element a_i, the total number of zeros $n^{=0}$ and the product of non-zero elements $y^{>0}$, one can uniquely compute $l_i \cdot r_i$.

Similar to the work on near-homomorphisms [13], we also observe that some non-invertible operations (such as multiplication) can be inverted by extending them to compute a (small) baggage of extra information.

We propose to extend the language to allow the user to connect an associative and commutative operator $\odot : \alpha \rightarrow \alpha \rightarrow \alpha$ with

- its associative and commutative lifted operator $\odot^L : \beta \rightarrow \beta \rightarrow \beta$ and its (left) inverse $\odot^L_{inv} : \beta \rightarrow \beta \rightarrow \beta$.[2]
- a pair of functions that convert between α and β, denoted $f^{>}_{\odot} : \alpha \rightarrow \beta$, and $f^{<}_{\odot} : \beta \rightarrow \alpha$.

The properties that the user must ensure are:

(1) $f^{<}_{\odot}\ \circ\ (\textbf{reduce}\ \odot^L\ e_{\odot^L})\ \circ\ (\textbf{map}\ f^{>}_{\odot})\ \ \equiv\ \ \textbf{reduce}\ \odot\ e_\odot$
(2) for sanity, $e_{\odot^L}$ must belong to the co-domain of $f^{>}_{\odot}$,
(3) $\forall\ a, b$ if $z = a\ \odot^L\ b$ then it holds that $a\ =\ z\ \odot^L_{inv}\ b$ and $b\ =\ z\ \odot^L_{inv}\ a$.

It can be derived from (1) and (2) that $e_{\odot^L} \equiv f^{>}_{\odot}(e_\odot)$, that $e_\odot \equiv f^{<}_{\odot}(e_{\odot^L})$ and that $f^{<}_{\odot} \circ f^{>}_{\odot} \equiv id$.

The lifted operators and conversions for multiplication are:

$$\begin{array}{rcl} (n^{=0}_1,\ y^{>0}_1)\ \cdot^L\ (n^{=0}_2,\ y^{>0}_2) & = & (n^{=0}_1 + n^{=0}_2,\ y^{>0}_1 \cdot y^{>0}_2) \\ (n^{=0}_1,\ y^{>0}_1)\ \cdot^L_{inv}\ (n^{=0}_2,\ y^{>0}_2) & = & (n^{=0}_1 - n^{=0}_2,\ y^{>0}_1 / y^{>0}_2) \end{array}$$

[2]We argue that this extension is reasonable since parallel languages commonly *assume* that the operators of reduce and scan are associative, and that those of reduce-by-index are also commutative. In fact, verification of such properties is undecidable in general.

$$\begin{array}{lcl} f^{>}_{\odot}\ (a_i) & = & \textbf{if}\ (a_i == 0)\ \textbf{then}\ (1,1)\ \textbf{else}\ (0,a_i) \\ f^{<}_{\odot}\ (n^{=0}, y^{>0}) & = & \textbf{if}\ (n^{=0} == 0)\ \textbf{then}\ y^{>0}\ \textbf{else}\ 0 \end{array}$$

Instead of differentiating **let** y = **reduce** $\odot$ $e_\odot$ as, the $\mathbb{VJP}$ transform would be applied to the semantically equivalent code:

$$\begin{array}{l} \textbf{let}\ as^L = \textbf{map}\ f^{>}_{\odot}\ as \\ \textbf{let}\ y^L = \textbf{reduce}\ \odot^L\ e_{\odot^L}\ as^L \\ \textbf{let}\ y = f^{<}_{\odot}\ y^L \end{array} \qquad (4)$$

and the code generation of the return sweep for the (middle) reduce statement will exploit the commutativity and invertibility of $\odot^L$:

```
let $\overline{as^L}$ $\overline{+}$=
  map2 ($\lambda$ $a^L$ $\rightarrow$ let $b^L$ = $y^L$ $\odot^L_{inv}$ $a^L$ in $\overline{\odot_{b^L}}^L$ $a^L$) $as^L$
    denoting $\overline{\odot_{b^L}}^L$ $\leftarrow$ $\mathbb{VJP}^{\text{LAM}}$ ($\lambda$ $x$ $\rightarrow$ $b^L$ $\odot^L$ $x$) $\overline{y^L}$
```

where $\overline{\odot_{b^L}}^L$ implements the differentiation of $y^L = b^L \odot^L a^L$ with respect to a^L according to core re-write rule 1, i.e.,

$$\overline{\odot_{b^L}}^L\ (a^L)\ \equiv\ \frac{\partial (b^L \odot a^L)}{\partial a^L} \cdot \overline{y^L}$$

An interesting example of associative, commutative and invertible operator that we are unaware to have been previously reported is:

$$\begin{array}{lcl} (p_1,\ s_1)\ \text{`sumOfProd`}\ (p_2,\ s_2) & = & (p_1 + p_2 + s_1 \cdot s_2,\ s_1 + s_2) \\ (p, s)\ \text{`sumOfProd`}_{inv}\ (p_2,\ s_2) & = & (p - p_2 - (s - s_2) \cdot s_2,\ s - s_2) \end{array}$$

For example, $\Sigma_{0 \le i < j < n}(a_i \cdot a_j)$ — where a_i and a_j denote different elements of an array as of length n — can be computed with:

$$\textbf{map}\ f^{>}_{\text{sumOfProd}}\ as\ \triangleright\ \textbf{reduce}\ \text{sumOfProd}\ (0,0)\ \triangleright\ f^{<}_{\text{sumOfProd}}$$

and efficiently differentiated, as shown above. The conversions of the corresponding *near-homomorphism* are:

$$\begin{array}{lcl} f^{>}_{\text{sumOfProd}}\ (a_i) & = & (0, a_i) \\ f^{<}_{\text{sumOfProd}}\ (p,\ \_) & = & p \end{array}$$

4 REVERSE-AD FOR REDUCE-BY-INDEX

We recall that reduce-by-index, a.k.a., multi-reduce, is a second-order array combinator that generalizes a histogram computation [17]: it reduces the values falling in the same bin with an arbitrary associative and commutative operator $\odot$, having neutral element $e_\odot$. Its type and sequential/imperative semantics are:

```
def reduce_by_index ∀ w,n.
            (hist: *[w]α) (⊙:α → α → α) (e⊙ : α)
            (ks:  [n]int) (vs:  [n]α) : *[w]α =
  for i = 0..n-1 do
      key = ks[i]
      if 0 <= key && key < w
        hist[key] = hist[key] ⊙ vs[i]
  return hist
```

To simplify the reverse-mode AD transformation we systematically re-write **let** statements of the kind:

```
let hist = reduce_by_index hist₀ ⊙ e⊙ ks vs
```

into the semantically-equivalent code:

```
let xs = reduce_by_index (replicate w e⊙)
                                    ⊙ e⊙ ks vs
let hist = map2 ⊙ hist₀ xs
```

that always applies **reduce_by_index** to an initial histogram consisting only of neutral elements $e_\odot$. In this form, the adjoints of the initial histogram `dst` are decoupled from the **reduce_by_index**, i.e., they are updated by the differentiation of the **map2**. This re-write is reasonable because the design of **reduce_by_index** is built on the assumption that the histogram length is (significantly) smaller than the length of the input.[3]

```
-- Assuming vs & ks of length n, and xs of length w
-- Primal trace is the same as original:
let xs = reduce_by_index (replicate w e⊙)
                             ⊙ e⊙ ks vs
-- Return sweep:
let (sks,svs,siota) = zip3 ks vs [0..n-1]
                      ▷ radixSortByFirst
                      ▷ unzip3
let flag_fwd = [0 .. n-1]
             ▷ map (λi → i==0 || sks[i-1]!=sks[i])
let flag_rev = [0 .. n-1]
             ▷ map (λi → i==0 || flag[n-i])
let ls = seg_scan$^{exc}$ ⊙ e⊙ flag_fwd svs
let rs = reverse svs
       ▷ seg_scan$^{exc}$ ⊙ e⊙ flag_rev
       ▷ reverse
let $\overline{svs}$ =
  map4 ($\lambda k_i$ $v_i$ $l_i$ $r_i$ →
          if $k_i$ < 0 || $k_i$ >= w
          then $0_\alpha$ -- the zero of the element type $\alpha$
          else $\overline{f_{l_i,r_i}}$ $v_i$
            denoting $\overline{f_{l_i,r_i}}$ ← $\mathbb{VJP}^{\text{LAM}}$ ($\lambda x \rightarrow l_i \odot x \odot r_i$) $\overline{xs}[k_i]$
       ) sks svs ls rs
-- scratch creates an uninitialized array.
let $\overline{vs}$ = scatter (scratch $\alpha$ n) siota $\overline{svs}$
       ▷ map2 ($\overline{+}$) $\overline{vs}$
```

Figure 4: Reverse AD re-write rule for reduce_by_index

4.1 General Case

We start by observing that reduce-by-index accepts a data-parallel work-efficient $O(n)$ implementation obtained for example by (radix) sorting the key-value pairs according to the keys (i.e., the indices in ks), and then by applying a segmented reduce to sum up (with $\odot$) each segment, where a segment corresponds to the (now consecutive) elements that share the same key value. A direct approach would be to apply the re-write above and differentiate the resulted code. The rationale for not taking this simple(r) path is because our differentiation of scan — which appears in the implementation of segmented reduce — is not work preserving (see Section 5.2).

Instead, the path we take builds on the one used in the general case of reduce. Adapting equation 2 to reduce-by-index results in:

$$\overline{v_i}\ \overline{+}= \frac{\partial\,(l_i\ \odot\ v_i\ \odot\ r_i)}{\partial\, v_i} \cdot \overline{x}_{k_i} \qquad (5)$$

[3] An asymptotic preserving re-write would be to replace the replicate with a scatter that writes $e_\odot$ only at the positions corresponding to the set of (unique) indices of ks. Similarly, map can be replaced with a gather-scatter that updates only those positions.

where v_i corresponds to `vs[i]`, l_i and r_i correspond to the forward and reverse partial sums (by $\odot$) of elements up to position i that have the same key k_i as element v_i, and $\overline{x}_{k_i}$ is the adjoint of element at index k_i in the resulted histogram. It follows that the implementation of 5 requires a multi-scan for computing l_i and r_i within the segment corresponding to elements sharing the same key k_i. This is commonly achieved by (radix) sorting the key-value pairs according to the keys. Figure 4 shows the asymptotic-preserving re-write rule that implements the reverse-mode differentiation:

- **lines 7-9** use a data-parallel implementation of radix sort ($O(n)$ work) to sort the key-value pairs (`sks`, `svs`) according to the keys; the implementation only sorts $[0, \ldots, n-1]$ according to keys, and then gathers vs according to the resulted `siota`.
- **lines 10-11** create the flag array that semantically partitions the sorted values (`svs`) into segments, such that all elements of a segment share the same key — a **`true`** value in the flag array correspond to the start of a segment.
- **line 14** performs a segmented scan, i.e., computes the (forward) prefix sum with operator $\odot$ for each segment.
- **lines 12-13 and 15-17** compute in a similar way the reverse scan for each segment.
- **lines 19-28** compute the adjoint contribution for each element of `vs` (in sorted order): if the index is out of the histogram bounds then the adjoint contribution is the zero value of the element type; otherwise the $\mathbb{VJP}$ code transformation is applied to generate the code for differentiating the function $\lambda\ x\ \rightarrow\ l_i\ \odot\ x\ \odot\ r_i$ at point v_i given the adjoint of the result $\overline{xs}[k_i]$ (where k_i denotes the key of v_i).
- **lines 32-33:** the adjoint contributions are permuted to match the original ordering (**`scatter`**) and added to the currently-known adjoint of `vs` (which corresponds to uses of `vs` after the **`reduce_by_index`** operation).

The shown algorithm is asymptotic preserving — all operations have work $O(n)$ — but it incurs a rather large (constant) overhead due to sorting. Reasons are twofold: (1) a sorting-approach to implementing generalized histograms has been shown to be several times slower than Futhark's **`reduce_by_index`**, even when using the state-of-the-art implementation of CUB library, and (2) Futhark's radix sort implementation we are using is between one-to-two order of magnitude slower than CUB's.

4.2 Specialized Rules

The reasoning used for the specialized cases of reduce also extends to reduce-by-index.

4.2.1 Addition. Specializing general rule 5 to addition results in:

$$\overline{v_i} \mathrel{+}= \frac{\partial\,(l_i\ +\ v_i\ +\ r_i)}{\partial\, v_i}\ \cdot\ \overline{x}_{k_i} \quad\Rightarrow\quad \overline{v_i} \mathrel{+}= \overline{x}_{k_i}$$

It follows that the primal remains identical with the original:

```
let xs = reduce_by_index (replicate w 0) (+) 0 ks vs
```

and the return sweep adds to the adjoint of each element of `vs` the adjoint of the histogram element corresponding to its key:

```
let v̄s = map2 (λ k → if k >= n then 0 else x̄s[k]) ks
       ▹ map2 (+) v̄s
```

The AD overhead should be under a factor of 2×.

```
let minᴸ (k₁, v₁) (k₂, (v₂) =
  if       v₁ < v₂ then (k₁, v₁)
  else if v₁ > v₂ then (k₂, v₂)
  else (min k₁ k₂, v1)

-- Assuming vs & ks of length n, and xs of length w
-- Original for min operator:
let rep∞ = replicate w ∞
let xs = reduce_by_index rep∞ min ∞ ks vs
-- Primal trace for min operator:
let rep₍ₙ,∞₎ = replicate w (n, ∞)
let (isₘᵢₙ,xs)= reduce_by_index rep₍ₙ,∞₎ minᴸ (n, ∞)
                            ks (zip [0,...n-1] vs) ▹ unzip
-- Return sweep for min operator:
let v̄s = map2 (λ iₘᵢₙ x̄ → if iₘᵢₙ >= n then 0_α
                             else v̄s[iₘᵢₙ] + x̄
              ) isₘᵢₙ x̄s
        ▹ scatter v̄s isₘᵢₙ
```

Figure 5: Reverse AD rule for reduce_by_index with min.

```
-- Assuming ⊙ with (left) inverse ⊙ᵢₙᵥ
-- Original is the same as primal:
let xs = reduce_by_index (replicate w e⊙) e⊙ ks vs

-- Return sweep:
let v̄s =
  ks vs ▹ map2(λkᵢ vᵢ → let bᵢ= xs[kᵢ] ⊙ᵢₙᵥ vᵢ in ⊙̄_bᵢ vᵢ)
              denoting ⊙̄_bᵢ ← VJP^LAM (λ x → bᵢ ⊙ x) x̄s[kᵢ]
           ▹ map2 (+̄) v̄s

-- A possible instantiation for ⊙ and ⊙ᵢₙᵥ:
let sumOfProd (p1, s1) (p2, s2) =
      (p1 + p2 + s1*s2, s1 + s2)
let sumOfProdᵢₙᵥ (p, s) (p2, s2) =
      (p - p2 - (s-s2)*s2, s - s2)
```

Figure 6: Reverse AD rule for reduce-by-index with operator that has a left inverse.

4.2.2 Min/Max. Figure 5 shows the re-write rule. The primal trace still consists of a reduce-by-index, but its operator is lifted to also compute the index of the minimal element ($\mathtt{min}^L$). The return sweep uses a scatter to update the adjoint of only the element that has produced the minimal value for that bin. In case of duplicates $\mathtt{min}^L$ selects the one at the smallest index in `vs`.

4.2.3 Multiplication. Specializing rule 5 to multiplication yields:

$$\overline{v_i}\ \mathrel{+}=\ \frac{\partial\,(l_i\ \cdot\ v_i\ \cdot\ r_i)}{\partial\, v_i}\ \cdot\ \overline{x}_{k_i} \quad\Rightarrow\quad \overline{v_i}\ \mathrel{+}=\ (l_i\ \cdot\ r_i)\cdot\ \overline{x}_{k_i}$$

Computing $l_i \cdot r_i$ can be achieved in a similar way as for reduction, by lifting the reduce by index (of the primal) to compute for each bin the number of zero and the product of non-zero elements falling in that bin. It follows that the lifted operator is (**`i64`**`.+`,α`.*`) for some numeric type α. The return sweep consists of a map that adds the contributions to the adjoint of `vs`.

4.2.4 *Invertible Operators.*

Similar to reduce, if the language would allow the user to specify the (left) inverse of an associative and commutative operator, then a re-write similar to 4 would enable a significantly more efficient differentiation rule — illustrated in figure 6 — than the general case, which is based on sorting.

4.2.5 *Vectorized Operators.*

Assuming $\odot : \alpha \rightarrow \alpha \rightarrow \alpha$, $e_\odot : \alpha$, $\texttt{h}^0 : \texttt{[w][d]}\alpha$, $ks : \texttt{[}n\texttt{]}\textbf{i64}$ and $vss : \texttt{[n][d]}\alpha$, the following re-write rule, named IRBIWIM, interchanges the **reduce_by_index** inside the **map** of a vectorized operator. This results in a segmented reduce-by-index which operates on elements of rank one smaller than the original, i.e., the new operator is $\odot$ instead of **map2** $(\odot)$:

$$\begin{array}{l}\textbf{reduce\_by\_index}\ \texttt{h}^0\ (\textbf{map2}\ \odot)\ (\textbf{replicate}\ \texttt{d}\ e_\odot)\ \texttt{ks vss} \\ \qquad\qquad\qquad \equiv \\ \textbf{map2}\ (\lambda\ \texttt{h}^0_{col}\ \texttt{vss}_{col} \rightarrow \\ \qquad \textbf{reduce\_by\_index}\ \texttt{h}^0_{col}\ \odot\ e_\odot\ ks\ \texttt{vss}_{col} \\ \quad)\ (\textbf{transpose}\ \texttt{h}^0)\ (\textbf{transpose}\ \texttt{vss})\ \triangleright\ \textbf{transpose}\end{array} \qquad (6)$$

We have implemented this re-write and we (always) differentiate the code resulted after its application.

4.2.6 *Discussing Performance.*

The design of the reduce-by-index construct [17] navigates the time-space tradeoff by employing

- a multi-histogram technique that is aimed at reducing the conflicts in shared (or global) memory by having groups of threads cooperatively building partial histograms, and
- a multi-pass technique that processes different partitions of the histogram at a time as a way to optimize trashing in the last-level cache.

In addition, reduce-by-index attempts to maintain the histogram(s) in scratchpad memory if possible, and it implements the best form of atomic update available on the hardware for the given datatype. For example (i) addition, min, max, multiplication have efficient hardware implementation accessible through primitives such as `atomicAdd`, (ii) datatypes that fit into 64-bits use CAS instructions, while (iii) the rest use mutex-base locking, which is quite expensive.

The AD overheads of the specialized cases of reduce-by-index (other than addition) are difficult to predict (or reason at a high level) because of the lifted operators. For example, `int32.min` is efficiently supported in hardware, but its lifting operates on `(int64,int32)` tuples and thus require mutex-based locking. Furthermore, the size of the element type is tripled, which restricts the multi-histogram degree and thus impedes the reduction of conflicts. For vectorized min, the tripling of the size might make it to not fit in scratchpad memory anymore. All these factors may result in a significant overhead that is not visible in the re-write rules.

5 REVERSE-AD FOR SCAN (PREFIX SUM)

Our differentiation of scan is restricted to operators that are defined on tuples of scalars of arbitrary dimension d, or to vectorized liftings of such operators, i.e., a tower of maps applied on top of such operators. Our algorithm manifests and multiplies $d \times d$ Jacobians, which is arguably asymptotically preserving since d is a constant but it is not AD efficient. Nevertheless, section 6.3 demonstrates that it still offers competitive performance on many practical cases.

Discussion is structured as follows: section 5.1 presents the step-by-step rationale used to derive the algorithm — which we found interesting because it combines dependence analysis on arrays with functional-style re-write rules — then section 5.2 puts together the algorithm, and section 5.3 presents several specializations that enable significant performance gains — e.g., vectorized operators and sparsity patterns — and concludes with a discussion that qualitatively compare our algorithm with the one of PPAD [44].

5.1 Deriving the Differentiation of Scan

An inclusive scan [6] computes all prefixes of an array by means of an associative operator $\odot$ with neutral element $e_\odot$:

```
let rs = scan ⊙ $e_\odot$[$a_0, \ldots, a_{n-1}$]
       ≡ [$a_0, a_0 \odot a_1, \ldots, a_0 \odot \ldots \odot a_{n-1}$]
```

While the derivation of (multi-) reduce builds on a functional-like high-level reasoning, in scan's case, we found it easier to reason in an imperative, low-level fashion. For simplicity we assume first that $\odot$ operates on real numbers, and generalize later:

```
rs[0] = as[0]
for i in 1 ... n-1 do
    rs[i] = rs[i-1] ⊙ as[i]
```

The loop above that implements scan, writes each element of the result array `rs` exactly once. To generate its return sweep, we can reason that we can fully unroll the loop, then apply the main rewrite-rule from equation 1 to each statement and finally gather them back into the loop. The unrolled loop is:

```
rs[0] = as[0]
rs[1] = rs[0] ⊙ as[1]
...
rs[n -1] = rs[n -2] ⊙ as[n -1]
```

The application of $\mathbb{VJP}$ to each statement results in return sweep:

```
$\overline{rs}$[n-2] = $\partial(rs[n-2] \odot as[n-1]) / \partial rs[n-2]$ * $\overline{rs}$[n-1]
$\overline{as}$[n-1] = $\partial(rs[n-2] \odot as[n-1]) / \partial as[n-1]$ * $\overline{rs}$[n-1]
...
$\overline{rs}$[0] = $\partial(rs[0] \odot as[1]) / \partial rs[0]$ * $\overline{rs}$[1]
$\overline{as}$[1] = $\partial(rs[0] \odot as[1]) / \partial as[1]$ * $\overline{rs}$[1]
$\overline{as}$[0] = $\overline{rs}$[0]
```

The differentiated statements can be rolled back to form the loop:

```
$\overline{rs}$ = copy $\overline{ys}$
for i = n-1 ... 1 do
    $\overline{rs}$[i-1] += $\partial(rs[i-1] \odot as[i]) / \partial rs[i-1]$ * $\overline{rs}$[i]
    $\overline{as}$[i]   += $\partial(rs[i-1] \odot as[i]) / \partial as[i]$ * $\overline{rs}$[i]
$\overline{as}$[0] += $\overline{rs}$[0]
```

where $\overline{ys}$ denotes the adjoint of `rs` corresponding to the uses of scan's result in the remaining of the program.

Simple dependence analysis, for example based on direction vectors, shows that the loop can be safely distributed across its two statements, since they are not in a dependency cycle:

```
$\overline{rs}$ = copy $\overline{ys}$
for i = n-1 ... 1 do
    $\overline{rs}$[i-1] += $\partial(rs[i-1] \odot as[i]) / \partial rs[i-1]$ * $\overline{rs}$[i]


for i = n-1 ... 0 do
    $\overline{as}$[i] += (i==0) ? $\overline{rs}$[0] :
                          $\partial(rs[i-1] \odot as[i]) / \partial as[i]$ * $\overline{rs}$[i]
```

```
1  -- We denote with n the length of as and with
2  --    d the dimensionality of the element type α
3  -- Primal trace is the same as the original:
4  let rs = scan ⊙ e⊙ as
5
6  -- Return sweep:
7  --   (1) computes cs (Jacobians):
8  let cs = map (λi → if i == n-1
9                      then I_d
10                     else J⃖⊙,as i rs[i]
11                  -- ^ i.e., ∂(rs[i] ⊙ as[i+1])/∂rs[i]
12               ) [0,...,n-1]
13   denoting J⃖⊙,as i x  =  (f_{0,i,⊙,as} x, ..., f_{d-1,i,⊙,as} x)
14          f_{k,i,⊙,as}  ←  VJP^LAM (λx → x ⊙ as[i+1]) (unitVec k)
15
16 --   (2) computes the adjoint of rs by means of
17 --       parallelizing a backward linear recurrence
18 let lin_o (b1,c1) (b2,c2) = (b2 + c2 · b1, c2 × c1)
19 let (r̅s̅, _) = zip (reverse y̅s̅) (reverse cs)
20              ▹ scan lin_o (0_d, I_d)
21              ▹ reverse ▹ unzip
22 --   (3) updates the adjoint of as by a map:
23 let a̅s̅ +=
24   map (λi r̅i̅ ai →
25          if i == 0 then r̅i̅
26          else g_{i,⊙} ai -- i.e., ∂(rs[i-1] ⊙ ai)/∂ai · r̅i̅
27          denoting g_{i,⊙} ← VJP^LAM (λx → rs[i-1] ⊙ x) r̅i̅
28      ) [0,...,n-1] r̅s̅ as
```

Figure 7: Reverse-AD Rule for Scan.

The second loop exhibits no cross iteration dependencies, hence the adjoints of as can be computed by a **map**. The first loop can be expressed by the backwards linear recurrence of form:

$$\overline{rs}_{n-1} = \overline{ys}_{n-1}$$
$$\overline{rs}_i = \overline{ys}_i + cs_i \cdot \overline{rs}_{i+1}, i \in n-2 \ldots 0$$

where cs is defined by $cs_{n-1} = 1$ and $cs_i = \partial(rs_i \odot as_{i+1}) / \partial rs_i$. Such a recurrence is known to be solved with a scan whose operator is linear-function composition [7].

5.2 Re-Write Rule for Arbitrary-Tuple Types

The reasoning used in the previous section generalizes to d-dimensional tuples (chosen for simplicity) of the same numeric type α, essentially by lifting scalar addition and multiplication to operate on vectors and matrices.[4] Figure 7 presents the proposed re-write rule.

For example, the linear-function composition operator has type $\texttt{lin}_o : (\alpha^d, \alpha^{d\times d}) \rightarrow (\alpha^d, \alpha^{d\times d}) \rightarrow (\alpha^d, \alpha^{d\times d})$ and $+$, $\cdot$ and $\times$ denote vector addition, vector-matrix and matrix-matrix multiplication, respectively, where vectors live in α^d (its zero is $\texttt{0}_d$) and matrices in $\alpha^{d\times d}$. Similarly, $cs_{i>0}$ are the $d \times d$ Jacobians corresponding to $\partial(rs_i \odot as_{i+1}) / \partial rs_i$ and $cs_0 = \mathbf{I_d}$ is the identity matrix.

[4]The reasoning generalizes also to tuples of heterogeneous scalar types.

The code for computing $cs_{i>0}$ — represented in figure 7 by means of $\overleftarrow{J}_{\odot,\texttt{as}}$ `i rs[i]` — is generated by applying the $\mathbb{JVP}^{\mathbb{LAM}}$ transformation to lambda $\lambda x \rightarrow x \odot as[i+1]$ and to each of the unit vectors (`unitVec k`, $k = 0 \ldots, d-1$) as the adjoint of the result.

The generated code consists of two kernels: one corresponding to the fusion of the map computing `cs` together with the reversion of `cs` and $\overline{ys}$ and the scan, and the second corresponding to the fusion of the reversion of $\overline{rs}$ with the map that updates $\overline{as}$.

5.3 Specializations

5.3.1 Addition. The return sweep of **let** `ys =` **scan** `(+) 0 as` is commonly known to be:

let $\overline{as}$ = **scan** (+) 0 (**reverse** $\overline{ys}$) ▹ **reverse** ▹ **map2** (+) 0 $\overline{as}$

This can also be derived from figure 7: $\partial($`rs[i] + as[i+1]`$)/\partial$`rs[i]` simplifies to 1, hence `cs =` **replicate** `n 1`, which means that we are composing linear functions of the form $f_{\overline{ys}_i}\ x = \overline{ys}_i + x$, which results in $\overline{rs}$ = **scan** (+) 0 (**reverse** $\overline{ys}$) ▹ **reverse**, and so on.

5.3.2 Vectorized Operators. Scans with vectorized operators are transformed to scans with scalar operators (whenever possible) by the (recursive) application of the Iswim rule[5] [19]:

$$\begin{array}{c}\textbf{scan}\ (\textbf{map2}\ \odot)\ (\textbf{replicate}\ \mathrm{n}\ e_\odot)\ \texttt{matrix} \\ \equiv \\ \textbf{map}\ (\textbf{scan}\ \odot\ e_\odot)\ (\textbf{transpose}\ \texttt{matrix})\ \triangleright\ \textbf{transpose}\end{array} \quad (7)$$

and differentiation is applied on the resulted code. This is essential because the "general-case" rule in figure 7 is *not* asymptotic preserving in the case of array datatypes due to the explicit manifestation and multiplication of Jacobians.

5.3.3 Block-Diagonal Sparsity (BDS). The expensive step in our rewrite rule of figure 7 is that entire $d \times d$ Jacobians corresponding to $\partial($`rs[i] + as[i+1]`$)/\partial$`rs[i]` (computed at line 10) are stored in `cs` and later multiplied inside (the scan with operator) $\texttt{lin}_o$ (line 18/20). It is not only that $\texttt{lin}_o$ takes $O(d^3)$ time, but more importantly, the size of the elements being scanned is proportional with d^2, which quickly restricts (i) the amount of efficient sequentialization, and ultimately (ii) the storing of intermediate data in scratchpad memory that is paramount for the GPU efficiency of scan.

In this sense, we have implemented (compiler) analysis to statically detect sparse Jacobians of block-diagonal form. More precisely, we consider the case of k blocks, where each block has size $q \times q$, hence $d = k \cdot q$. Multiplication preserves the block-diagonal shape:

$$\begin{bmatrix} \mathbf{M}^1_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{M}^1_\mathbf{k} \end{bmatrix} \times \begin{bmatrix} \mathbf{M}^2_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{M}^2_\mathbf{k} \end{bmatrix} = \begin{bmatrix} \mathbf{M}^1_1 \times \mathbf{M}^2_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{M}^1_\mathbf{k} \times \mathbf{M}^2_\mathbf{k} \end{bmatrix}$$

We multiply such a matrix with v, a vector of length d as such:

$$\begin{bmatrix} \mathbf{v_1}, & \cdots, & \mathbf{v_k} \end{bmatrix} \times \begin{bmatrix} \mathbf{M_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{M_k} \end{bmatrix} = \begin{bmatrix} \mathbf{v_1} \times \mathbf{M_1} \\ \vdots \\ \mathbf{v_k} \times \mathbf{M_k} \end{bmatrix}$$

If `cs` has the BDS pattern, then, semantically, we shrink its representation down to a tuple of k arrays each of dimension $n \times (q \times q)$

[5]Iswim states that summing up the elements of each column of a matrix can be achieved by transposing the matrix, summing up each row and transposing back the result.

and similarly, $\overline{ys}$ to a tuple of k arrays of dimension $n \times q$.[6] The computation of $\overline{\texttt{rs}}$ is performed with k different scans, each of them using a scaled-down (adjusted) operator $\texttt{lin}_o^{BDS}$ that is semantically defined on elements of type $(\alpha^q, \alpha^{q\times q})$ — the corresponding vector- and matrix-matrix multiplications inside $\texttt{lin}_o^{BDS}$ are performed as shown above. This reduces the element size of the scanned array, enabling better utilization of scratchpad memory.

5.3.4 Redundant Block-Diagonal (RBDS) Sparsity. The case when the block-diagonal sparsity has the additional property that all the blocks hold identical values, i.e., $M_1 = M_2 = \ldots = M_k$, allows an even more efficient implementation: The representation of `cs` is shrunk down to (semantically) one array of dimension $n \times (q \times q)$ and only one scan is performed. $\texttt{lin}_o^{RBDS}$ now operates on elements of type $(\alpha^d, \alpha^{q\times q})$ and it performs ***one multiplication of*** $q \times q$ ***matrices***, and k vector-matrix multiplications $\mathbf{V^q} \times M^{q\times q}$:

$$\begin{bmatrix}\mathbf{v_1}, & \cdots, & \mathbf{v_k}\end{bmatrix} \times \begin{bmatrix}\mathbf{M} & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & \mathbf{M}\end{bmatrix} = \begin{bmatrix}\mathbf{v_1} \times \mathbf{M}\\ \vdots\\ \mathbf{v_k} \times \mathbf{M}\end{bmatrix}$$

RBD sparsity has important applications: differentiating the multiplication of two $q \times q$ matrices $A \times B$ with respect to A (or B), results in a Jacobian that consists of q blocks of size $q \times q$, in which each block is equal to B (or A), i.e., the Jacobian of $\partial(A \times B)/\partial A$ is:

$$\begin{bmatrix}B & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & B\end{bmatrix}$$

This is important because the scan with $q \times q$ matrix multiplication is commonly used to parallelize linear recurrences of degree q [7], i.e., $x_i = a_i^0 + a_i^1 * x_{i-1} + \ldots + a_i^q * x_{i-q+1}$.

Similarly, differentiating the (classical) linear function composition with respect to the first argument also results in RBS sparsity, i.e., $\partial(b_2 + c_2 \cdot b_1, c2 \cdot c1)/\partial(b_1, c_1)$ has Jacobian $\begin{bmatrix}c_2 & 0\\ 0 & c_2\end{bmatrix}$

5.3.5 Discussion. Our "general-case" rule for scan computes and multiplies $d \times d$ Jacobians. While this arguably preserves the work asymptotic (d is a constant for tuples), it is not AD efficient[7] and it is theoretically inferior to the re-write rule of PPAD [44] — shown in figure 11 in Appendix — which uses only the $\mathbb{VJP}$ transformation, thus avoiding operating with (full) Jacobians.

Our "general-case" rules is however faster than PPAD when the dimensionality d is one, and the vectorized-operator and RBDS specializations makes it also more effective on many operators of practical interest, with speed-ups commonly ranging from $1.2\times$ $-2.25\times$ (vs **Cmp**), as reported in section 6.3.

However, the PPAD algorithm benefits significantly from a recent and novel improvement to dead-code elimination (DCE) that we have designed — which we are not aware to have been proposed in any other compiler. In a system supporting the Iswim transformation (for vectorized operators) and the DCE improvement, PPAD's

[6]Since the original scan operator is defined on tuples of scalars and Futhark compiler uses a tuple of array representation, it follows that in practice, `cs` is represented as $k \cdot q \cdot q$ arrays of length n, that we tuple differently at no runtime overhead. Similar thoughts apply to $\overline{ys}$ and $\texttt{lin}_o^{BDS}$, i.e., $\texttt{lin}_o^{BDS}$ still operates on tuples of scalars.

[7]There is no constant factor independent of the program that bounds the AD overhead.

```
def linFnComp (b1:f32, c1:f32) (b2:f32, c2:f32) =
      (b2 + c2*b1,    c2 * c1)
def sumOfProd (p1:f32, s1:f32) (p2:f32, s2:f32) =
      (p1 + p2 + s1*s2,    s1 + s2)

def matMul2x2 (a1:f32, b1:f32, c1:f32, d1:f32)
              (a2:f32, b2:f32, c2:f32, d2:f32) =
      ( a1*a2 + b1*c2,    a1*b2 + b1*d2
      , c1*a2 + d1*c2,    c1*b2 + d1*d2 )
-- ^ matMul3x3, and matMul5x5 are similarly defined

def satAdd (x: f32) (y: f32) : f32 =
      if (x+y) > 1000000 then 1000000 else x+y
```

Figure 8: Non standard operators used in evaluation.

scan algorithm narrows the performance gap, and constitutes a simple and efficient solution for the cases when the element dimensionality is greater than one (albeit it is still slightly slower than our solution when the scan operator exhibits RBD sparsity).

Finally, for the un-vectorized operators that use array arguments, we postulate that a more suited strategy would be to differentiate the classical work-preserving (two-stage) implementation of scan [6] written in terms of loop, map and scatter operations.

6 EXPERIMENTAL EVALUATION

The discussion is structured as follows: section 6.1 presents the evaluation methodology and sections 6.2 ,6.3 and 6.4 evaluate the performance of reverse-mode differentiation of reduce, scan and reduce-by-index, respectively.

6.1 Operators, Datasets, Methodology

The evaluation uses randomly generated arrays and single-precision float as the base numeric type.

6.1.1 Operators. The evaluated operators are: (i) standard addition (+), multiplication (*), and min, (ii) their vectorized forms, e.g., **`map2`** `(*)`, (iii) 2×2, 3×3 and 5×5 matrix multiplication, e.g., which is used in the parallel implementation of linear recurrences, (iv) linear function composition, (v) sum of products, and (vi) saturated addition. For convenience, figure 8 shows the non-standard ones. Of note, linear function composition and matrix multiplication are only associative but not commutative, hence they are not valid operators for reduce-by-index, which requires commutativity.

6.1.2 Datasets. The evaluation of reduce and scan uses two datasets denoted by D_1 and D_2:

map2 (*): For vectorized multiplication, D_1 and D_2 correspond to arrays of dimensions $10^6 \times 16$ and $10^7 \times 16$, respectively, which are provided in transposed form.

matMul5x5: For 5×5 matrix multiplication, D_1 corresponds to 10 million elements – each element is a tuple of arity 25 – and D_2 corresponds to 50 million elements.

For the others D_1 and D_2 correspond to 10 million and 100 million elements, e.g., the element for sum-of-products is a tuple of floats (arity 2).

The evaluation of reduce-by-index uses six datasets denoted by $D_{i,j}$ where $i = 1, 2$ refers to the number of elements in the input arrays (10^7 and 10^8) and $j = 1, 2, 3$ refers to the number of elements in the resulting histogram (31, 401 and 500000, respectively). When the operators are vectorized, the number of elements are kept the same, e.g., $i = 1$ corresponds to 10^6 elements, each of dimension 10, and $j = 2$ to a histogram of 401 elements, each of dimension 10.

6.1.3 Hardware, Software and Competitor. Benchmarks are run on an Nvidia A100 40GB PCIe GPU with listed peak memory bandwidth of **1555 Gb/sec**. We compare the performance of our technique (**Our**) for reduce and scan with the algorithms presented in PPAD [44] (**Cmp**), which we have implemented in Futhark.

A recent novel improvement to dead-code elimination—which we are not aware to exist in any other compiler—has significantly improved the performance of PPAD (since the time this paper was developed). For fairness, we present the competitor's performance with (**Cmp***) and without this improvement (**Cmp**).[8].

6.1.4 Methodology. We measure the total application running time, but *excluding* the time needed to transfer the program input and (final) result between device and host memory spaces. We report the average of at least 25 runs — or as many as are needed for a 95% confidence interval to be reached.

The performance of the primal (original program) is reported as memory throughput, measured in **Gb/sec**. Denoting with n the length of the input array and with β the size of the array element type, the total number of bytes `Nbytes` is computed as follows:

$$\texttt{Nbytes} = \begin{cases} n \cdot \texttt{sizeof}(\beta), & \text{for reduce} \\ 2 \cdot n \cdot \texttt{sizeof}(\beta), & \text{for scan} \\ 3 \cdot n \cdot \texttt{sizeof}(\beta) + n \cdot 8, & \text{for reduce-by-index} \end{cases} \tag{8}$$

For reduce and scan these are the minimal number of bytes that needs to be accessed from global memory, e.g., reduce needs to read each element once. For reduce by index we reason that:

(1) reading the input array requires $n \cdot \texttt{sizeof}(\beta)$ bytes,
(2) reading the key requires $n \cdot 8$ bytes, because the key is represented as a 64-bit integer,
(3) updating the histogram *may* require a read and a write access, hence another $2 \cdot n \cdot \texttt{sizeof}(\beta)$ bytes.

For the primal, histograms of sizes 31 and 401 typically fit in scratchpad (shared/fast) memory, but histograms of size 50000 do not and are stored in global memory. It follows that we choose to consider the accesses that update the histogram in order to be able to meaningfully compare across different datasets and implementations — i.e., our measure of memory throughput is essentially a normalized runtime. The consequence is that on small histograms the reported **Gb/sec** may exceed the peak memory bandwidth of the hardware, because the histogram is maintained in shared memory.

The performance of the differentiated code — that computes both the primal and the adjoint results — is presented in terms of AD overhead, which is defined as the ratio between the running times of the derivative and primal (original) – the lower the better.

[8]The branch of the Futhark compiler that was used for this paper and that does not contain the advanced treatment of dead-code elimination is available at https://github.com/diku-dk/futhark/tree/ihwim-ifl23

6.2 Reduce

The top of figure 9 presents the performance of the primal and reverse-mode differentiation of reduce on the evaluated operators and datasets. Column **Our** reports the AD overhead of our approach, and columns **Cmp*** and **Cmp** report the AD overhead of the competitor [44], with and without the aggressive treatment of dead-code elimination, respectively. The main observations are:

- In most cases, e.g., $+, \cdot,$ `min`, D_1 is too small to overcome the "system" overheads, resulting in sub-optimal performance of about half the peak bandwidth, e.g., the total runtime is about 53 micro-seconds μs for min, and launching the kernel takes ten(s) μs. Matters are much improved on the larger D_2.
- The specializations for $+, \cdot,$ `min` enable efficient differentiation — all AD overheads are under 3×. The case of multiplication highlights the impact of specialization: it offers 2.6–3.3× speedup in comparison to **Cmp***.
- linFnComp and sumOfProd are treated with the general-case algorithm and result in larger overheads 3.3–5.6×.
- Applying by hand the specialization for invertible operators to sumOfProd — see section 3.3 — results in AD overheads of 1.7× and 2.2× for D_1 and D_2, which offers good efficiency.
- The impact of the Irwim rule (see re-write 3) is highlighted by the case of vectorized multiplication: the AD overhead is under 4× and reasonably close to that of multiplication. In comparison, PPAD (**Cmp/Cmp***) has overheads of 784× and 467× on D_2, because it differentiates such a reduction by means of scans whose operators are defined on arrays but are not vectorized (which are ill supported by Futhark).
- Matrix multiplication triggers our general-case algorithm that (i) offers reasonable AD overheads 4.8–7.8× and (ii) is between 2–5.2× and 1.5–2.4× faster than **Cmp** and **Cmp***.
- in all tested cases our algorithm for reduce is faster than PPAD — this is not surprising since our algorithm is AD efficient, while PPAD's piggybacks on the algorithm for scan, which is claimed to not be AD efficient.

6.3 Scan

The bottom of figure 9 presents the performance of scan:

- The specialized rule for addition results in small AD overheads of under 1.8×. Min and multiplication are treated with the general-case rule (arity 1), but min is competitive with addition and multiplication has overheads under 3.8×.
- The operators defined on tuples of arity 2, namely `linFnComp` and `sumOfProd` still offer decent AD overheads of under 5.1×, where `linFnComp` is more efficient because it benefits from the optimization of RBD sparsity, discussed in section 5.3.4.
- The application of Iswim (see re-write 7) for vectorized multiplication has high impact, resulting in AD overheads under 0.6×, which suggests that Futhark compiler should always apply it. In comparison, **Cmp** and **Cmp*** are 56× and 31× slower, for reasons similar to the ones discussed for reduce.
- For matrix multiplication, which benefits from the RBD sparsity optimization, the AD overhead reaches a peak of 7.9× for 3×3 matrices, but then decreases for 4×4 and 5×5 matrices to an AD overhead of 4.1×, which indicates that performance remains a constant factor away from the primal.

Op	`reduce (+)`				`reduce min`				`reduce (*)`			
	Prim	**Our**	**Cmp**	**Cmp***	**Prim**	**Our**	**Cmp**	**Cmp***	**Prim**	**Our**	**Cmp**	**Cmp***
	Gb/s	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$
D_1	667	1.0×			741	2.5×			741	2.4×	6.3×	6.3×
D_2	1270	1.5×			1290	2.6×			1294	2.9×	9.7×	9.7×

Op	`reduce linFnComp`				`reduce sumOfProd`				`reduce (map2(*))`			
D_1	548	3.3×	8.6×	5.5×	792	3.7×	12.1×	6.7×	928	3.1×	610×	391×
D_2	759	4.1×	11.4×	6.8×	1314	5.6×	19.3×	10.3×	1328	3.7×	784×	467×

Op	`reduce matMul2x2`				`reduce matMul3x3`				`reduce matMul5x5`			
D_1	623	4.8×	9.4×	7.5×	675	6.4×	22.2×	15.1×	253	6.3×	33.0×	10.9×
D_2	869	6.4×	12.8×	9.9×	857	7.8×	27.9×	18.7×	269	6.7×	35.0×	11.8×

Op	`scan (+)`				`scan min`				`scan (*)`			
	Prim	**Our**	**Cmp**	**Cmp***	**Prim**	**Our**	**Cmp**	**Cmp***	**Prim**	**Our**	**Cmp**	**Cmp***
	Gb/s	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD-F}}{\text{Prim}}$	$\frac{\text{AD-C}}{\text{Prim}}$	$\frac{\text{AD-C}^*}{\text{Prim}}$
D_1	602	1.2×			689	1.3×	4.6×	4.6×	691	3.3×	4.9×	4.0×
D_2	1035	1.8×			872	1.4×	5.1×	5.1×	918	3.8×	5.7×	4.5×

Op	`scan linFnComp`				`scan sumOfProd`				`scan (map2(*))`			
D_1	856	3.3×	6.3×	3.9×	856	4.5×	6.1×	3.3×	103	0.58×	34.0×	19.8×
D_2	1030	3.7×	7.5×	4.3×	1031	5.1×	6.8×	3.7×	115	0.6×	33.8×	18.8×

Op	`scan matMul2x2`				`scan matmul3x3`				`scan matMul5x5`			
D_1	889	4.0×	6.3×	5.2×	805	7.6×	13.6×	8.1×	247	4.1×	8.2×	4.2×
D_2	1077	4.6×	7.5×	5.5×	841	7.9×	14.0×	8.4×	247	4.1×	8.2×	4.3×

Figure 9: Performance of the reverse-mode differentiation of `reduce` and `scan`. The performance of the original program (primal) is measured in Gb/sec and is reported in column Prim. AD performance is reported as AD Overhead, i.e., the ratio between the differentiated and primal runtimes (the lower the better). Column Our reports the AD overhead of our approach. Columns Cmp* and Cmp report the AD overhead of the competitor technique of PPAD [44] with (*) and without the application of the aggressive dead-code elimination optimization that we have implemented—our approach does not benefit from it.

- Our algorithm is significantly faster than **Cmp** in all evaluated cases. However, the improvement to dead-code elimination (DCE) allows **Cmp*** to significantly narrow the performance gap, and even to win in the case of `sumOfProd`, albeit it is still significantly slower on arity-1 operators (`min`,`*`). We surmise that PPAD scan's algorithm is a simple and effective solution for operators of arity greater than one (in a system that supports ISWIM and the DCE improvement).

6.4 Reduce By Index

Figure 10 shows the performance of differentiating reduce-by-index. We do not use a competitor since we are not aware of work on differentiating this construct at a high-level. Key observations are:

- The base cases (+,∗,`min`) are efficiently differentiated with overheads of at most 2.6×, except for `min` on $D_{1,3}$ and $D_{2,3}$, which corresponds to the largest histogram of length 500K that fits only in global memory. The slowdown is due to the lifted operator requiring a mutex lock instead of efficient atomic primitives as with the other two (`atomicAdd`/`Mul`).
- Vectorized operators incur larger overheads, due to reasons similar to the ones discussed for `min` (see also section 4.2.6). Without Irbiwim (see re-write 6), the **`map2`** `(*)` operator would result in a column of much-larger AD overheads: $[3.9\times, 3.7\times, 4.5\times, 8.5\times, 8.9\times, 12.4\times]^T$ (and similar for `min`).

Op	`(+)`		**`map2`** `(+)`		`min`		**`map2`** `min`	
	Prim	**OV**	**Prim**	**OV**	**Prim**	**OV**	**Prim**	**OV**
	Gb/s	$\frac{\text{AD}}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD}}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD}}{\text{Prim}}$	**Gb/s**	$\frac{\text{AD}}{\text{Prim}}$
$D_{1,1}$	1139	1.5×	612	1.7×	1120	1.8×	614	2.6×
$D_{1,2}$	1179	1.6×	548	1.6×	1146	1.9×	560	2.6×
$D_{1,3}$	803	1.6×	134	0.7×	321	2.9×	64	2.6×
$D_{2,1}$	1942	1.9×	984	2.5×	1951	2.1×	1041	3.4×
$D_{2,2}$	1939	1.9×	959	2.5×	1944	2.1×	1014	3.4×
$D_{2,3}$	883	1.6×	165	0.8×	344	3.9×	87	2.9×

Op	`(*)`		**`map2`** `(*)`		`sumOfProd`		`satAdd`	
$D_{1,1}$	1212	2.1×	633	2.9×	1451	31.0×	947	24.8×
$D_{1,2}$	1199	2.1×	543	2.8×	1412	45.8×	1176	45.6×
$D_{1,3}$	302	2.6×	63	2.9×	163	9.2×	302	21.2×
$D_{2,1}$	1955	2.4×	1019	3.5×	1672	35.2×	1947	50.6×
$D_{2,2}$	1953	2.5×	982	3.5×	1723	59.2×	1937	81.2×
$D_{2,3}$	265	2.0×	80	1.7×	122	7.3×	258	19.0×

Figure 10: Reverse-AD Performance of `reduce_by_index`.

- `sumOfProd` and `satAdd` are dispatched to the general-case algorithm that involves sorting and is inefficient, resulting in AD overheads as high as 81×. The rationale behind this is discussed at the end of section 4.1. An obvious optimization would be to improve the underlying sorting implementation.

- Supporting the invertible-operator refinement, discussed in section 4.2.4 and applied by hand to `sumOfProd`, results in very efficient differentiation, i.e. the following column of AD overheads: $[1.8\times, 1.7\times, 1.2\times, 1.8\times, 1.8\times, 1.1\times]^T$.

7 RELATED WORK

The most related work is the one of PPAD [44] that presents algorithms for high-level reverse-mode differentiation of reduce and scan. We have compared with it throughout the paper: Essentially our treatment of reduce is superior, as ours is AD efficient, and their treatment of scan is theoretically superior and also practically superior when the element's arity is greater than one and when the operator lacks RBD sparsity.

A body of work has investigated how to differentiate (parallel) functional array languages at a high level, i.e., before parallelism is mapped to the hardware. Dex [43] uses a technique where the program is first linearized, producing a linear map, then this linear map is transposed producing the adjoint code. Dex supports accumulators, which are discriminated by the type system, intuitively, into parallel or sequential loops, but does not support second-order parallel constructs such as scan and reduce-by-index.

$\widetilde{F}$ [51] proposes an AD implementation that is applied to a nested-parallel program and uses the forward mode, along with rewrite rules for exploiting sparsity in certain cases. DiffSharp [4] is a library for AD that aims to make available to the machine learning (ML) community, in convenient form, a range of AD techniques, including, among others, nesting of forward/reverse mode AD operations, efficient linear algebra primitives, and a functional API that emphasizes the use of higher-order functions and composition.

PRAD [26] is a parallel algorithm for reverse-mode AD of recursive fork-join programs that (i) is provably work efficient, (ii) has span within a polylogarithmic factor of the original program, and (iii) supports Cilk fork-joint parallelism, without requiring parallel annotations. Evaluated on 8 ML applications, PRAD is reported to achieve 1.5× AD overhead and 8.9× speedup on 18 cores.

None of these approaches propose specific AD algorithms for differentiating reduce, scan or reduce-by-index. The algorithms presented in this paper are part of Futhark's AD system [50], that supports (forward and) reverse-mode differentiation of nested-parallel programs. The key difference is that reverse-AD avoids using tape by a redundant-execution technique and by techniques that are aimed to rely on dependence analysis of loops [38, 39]. The AD implementation benefits from various compiler optimizations [16, 19, 20, 22, 34, 35] and specialized code generation [17, 18, 27, 36].

Another rich body of work refers to the implementation of AD algorithms in the imperative context, where parallelism is already mapped to hardware, e.g, by means of low-level APIs such as OpenMP and Cuda. Enzyme [31] applies AD on low-level compiler representation, thus taking advantage of both pre- and post-AD compiler optimizations. Since the support for AD is built in the low-level compiler (LLVM), their approach naturally achieves AD interoperability [33] across languages, e.g., Julia, and parallel APIs, such as OpenMP, MPI and Cuda. In particular, the AD algorithm for Cuda [32] makes use of AD-specific GPU memory optimizations including caching tape values in thread-local storage as well as memory-aware adjoint updates. However, we speculate that if the target Cuda kernels is already maxed out in terms of resource usage then the tape would need to be mapped in global memory, which will degrade the AD performance. This is typically the case for the kernels generated from reduce(-by-index) and especially scan [10, 36], which uses a single-pass implementation [30]. Reversely, Enzyme's low-level approach of differentiating memory would likely offer better performance for cases such as reduce-by-index with non-invertible operators (e.g., `satAdd`).

In the context of parallel API such as OpenMP and MPI, other reverse-AD implementations have been proposed, either by compiler transformations [25] or by overloading techniques [47, 48].

Reverse AD has also been implemented in DSLs for stencil computations [24], and tensor languages [5] that support constrained forms of loops, which do not require the use of tapes.

ML practitioners use tools such as Tensorflow [1], PyTorch [42] or JAX [8, 11] that restrict the programming interface, but offer well-tuned primitives for AI. A practically important direction is to promote AD interoperability across popular languages [40, 41], which bears similarities to prior work on supporting generics in computer algebra [9].

Finally, the time-space tradeoff for reverse-mode AD is systematically studied by Siskind and Pearlmutter [52], and Tapenade [2] supports a wealth of checkpointing techniques. Other approaches aimed at sequential code include ADOL-C [14], and Stalingrad [45].

In conclusion, none of the imperative or functional approaches (other than PPAD) have proposed AD algorithms specific to reduce, scan and reduce-by-index, or evaluated them for GPU execution.

8 CONCLUSIONS

We have presented reverse-mode differentiation algorithms for reduce, scan and reduce-by-index second-order parallel array combinators. Interestingly, the general-case algorithm re-writes the differentiation of a construct in terms of other, less-efficient ones: reduce's re-write uses scans, reduce-by-index uses multi-scan (implemented by sorting), and scan's re-write is not AD efficient.

However, we have also shown that for most cases of practical interest, specializations that enable efficient differentiation are possible: (i) vectorized operators are reduced to scalar ones and then differentiated, (ii) invertible operators allow reduce(-by-index) to be differentiated in terms of map/reduce-by-index constructs, and (iii) sparsity optimization allows reasonably-efficient differentiation of scans with (tuple-based) matrix-multiplication operators, which seem to remain a constant-factor away from the primal.

Most important, we have reported, to our knowledge, the first evaluation of reverse AD of said constructs in the context of GPU execution, which constitutes a useful baseline for future work.

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```
def op_bar_1 't (op : t → t → t)
                (x: t, y: t, r_b: t) : t =
  let op' b a = op a b in  vjp (op' y) x r_b

def op_bar_2 't (op : t → t → t)
                (x: t, y: t, r_b: t) : t =
  vjp (op x) y r_b

def op_lft 't (plus: t → t → t) (op : t → t → t)
              (x1: t, a1: t, y1_h: t)
              (_x2: t, a2: t, y2_h: t) : (t, t, t) =
  let z = plus (op_bar_1 op (x1, a1, y2_h)) y1_h
  in  (x1, op a1 a2, z)

def scan_bar [n] 't (zero: t) (plus: t → t → t)
       (op :  t → t → t) (e : t) (u : [n]t)
       (x_b : [n]t) : [n]t =
  let x = scan op e u
  let u_lft = map (λi → if i<n-1 then u[i+1] else e)
                  (iota n)
  let m = zip3 x u_lft x_b
  let (_, _, x_hat) = unzip3 <|
        scan_right (op_lft plus op) (e, e, zero) m
  let x_rht = map (λi → if i==0 then e else x[i-1])
                  (iota n)
  in  map (op_bar_2 op) (zip3 x_rht u x_hat)
```

Figure 11: Futhark Implementation of PPAD [44] Reverse-AD Rule for Scan

9 APPENDIX

For completeness, figure 11 shows the Futhark implementation of the PPAD rule for reverse differentiating scan [44], which we have used in our evaluation.