

Support for Parallel Scan in OpenMP

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24 April 2018

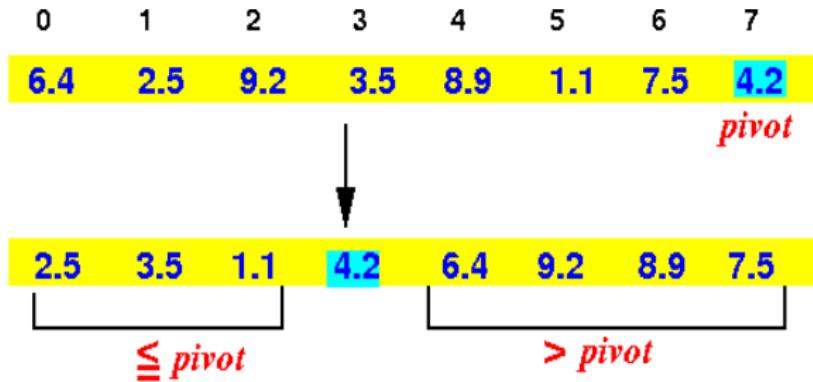
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Parallel Quicksort Algorithm



How can we do this in parallel?

Prefix Sums Problem

In computer science, the prefix sum, cumulative sum, inclusive scan or simply scan is defined as:

- Given a **binary associative operator** \oplus ;
- An ordered set of n elements $[a_0, a_1, \dots, a_{n-1}]$;
- Return the ordered set $[a_0, a_0 \oplus a_1, \dots, a_0 \oplus a_1 \oplus \dots \oplus a_{n-1}]$.

Prefix Sums Problem

There are two versions of Prefix Scan: inclusive and exclusive.

[3 1 7 0 4 1 6 3]



Inclusive [3 4 11 11 15 16 22 25]

Exclusive [0 3 4 11 11 15 16 22]

Prefix Sums Problem

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[3 1 7 0 4 1 6 3]

Inclusive [3 4 11 11 15 16 22 25]

→ Exclusive [0 3 4 11 11 15 16 22]

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Algorithm (Proposed by Horn in 2005)

Based in Hillis and Steele Work (1986).

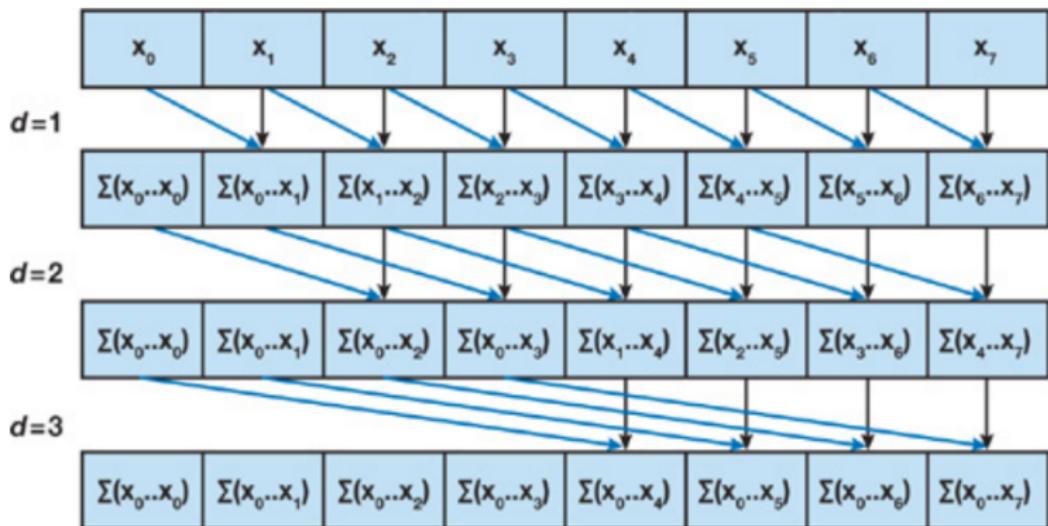


Figure 1: An illustration of the algorithm proposed by Horn

Complexity Analysis

The algorithm performs $O(n \log_2 n)$ addition operations.

- The tree has $\log_2 n$ levels;
- It is performed $O(n)$ adds for each level;

Remember that a sequential scan performs $O(n)$ adds. Therefore, this naive implementation is not work-efficient. The factor of $\log_2 n$ can have a large effect on performance.

Algorithm (Proposed by Mark Harris in 2007)

Based in Blelloch's Work (1990);

Two phases (Up-Sweep & Down-Sweep):

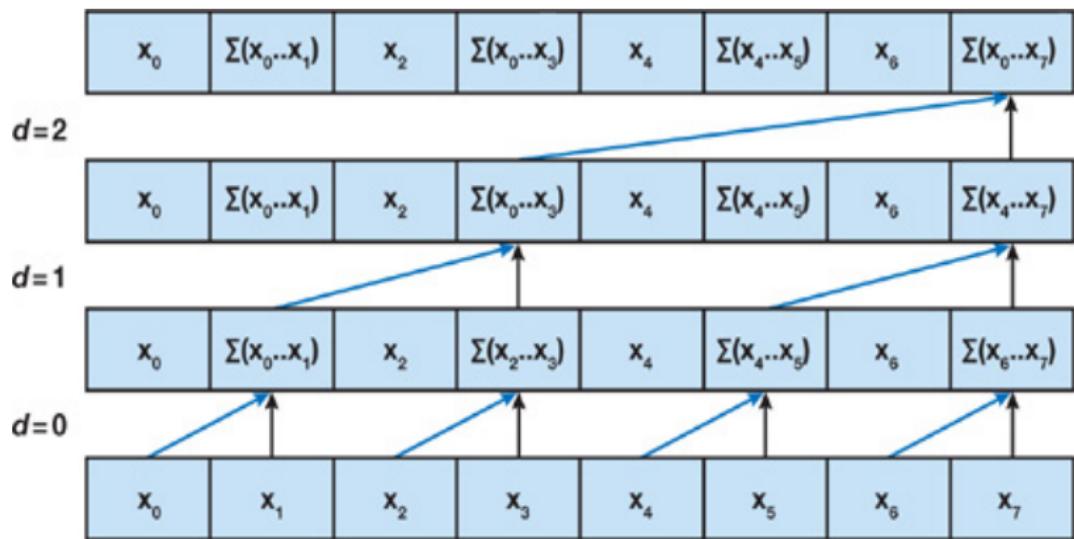
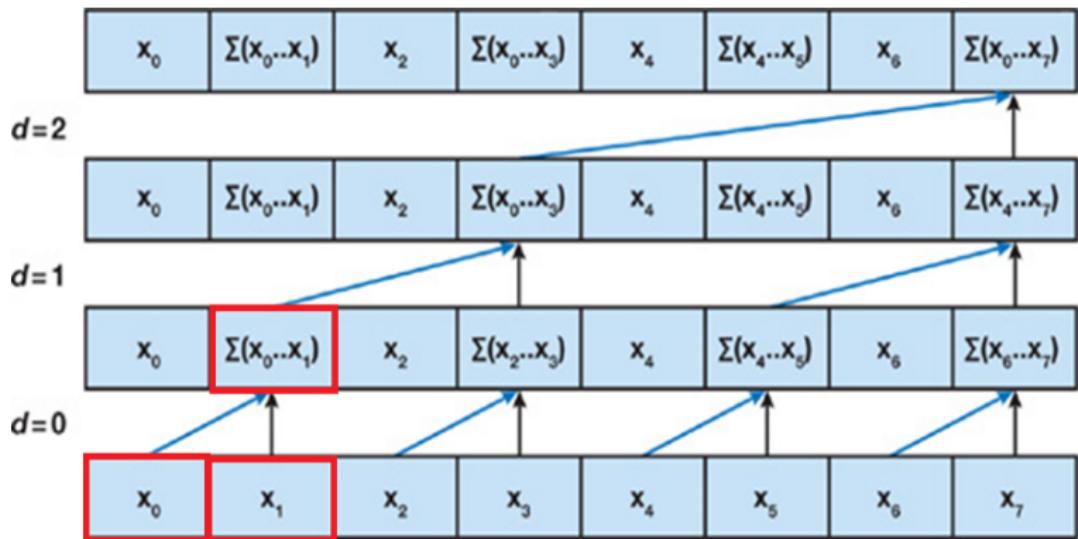
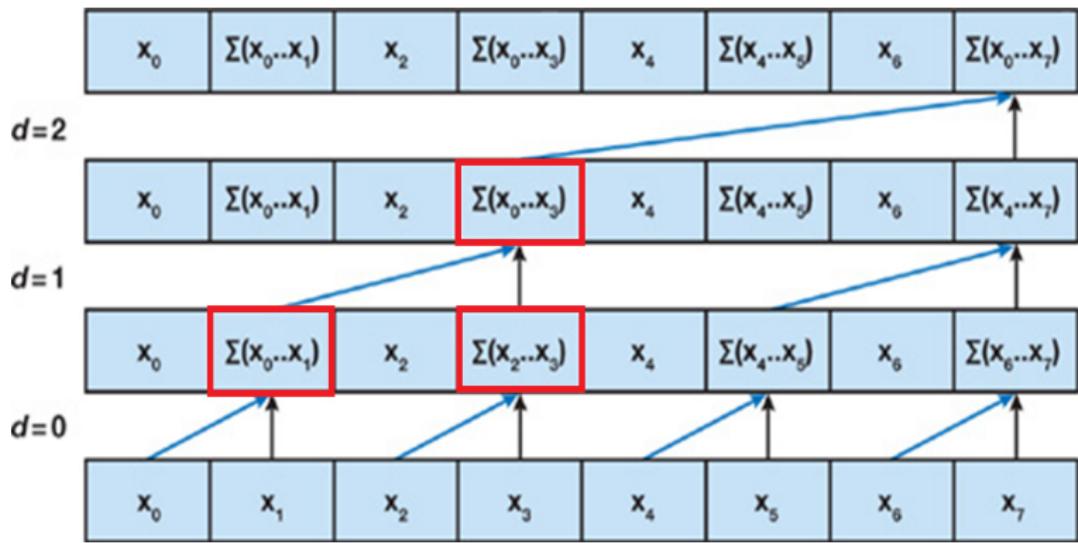


Figure 2: An illustration of the **Up-Sweep** phase

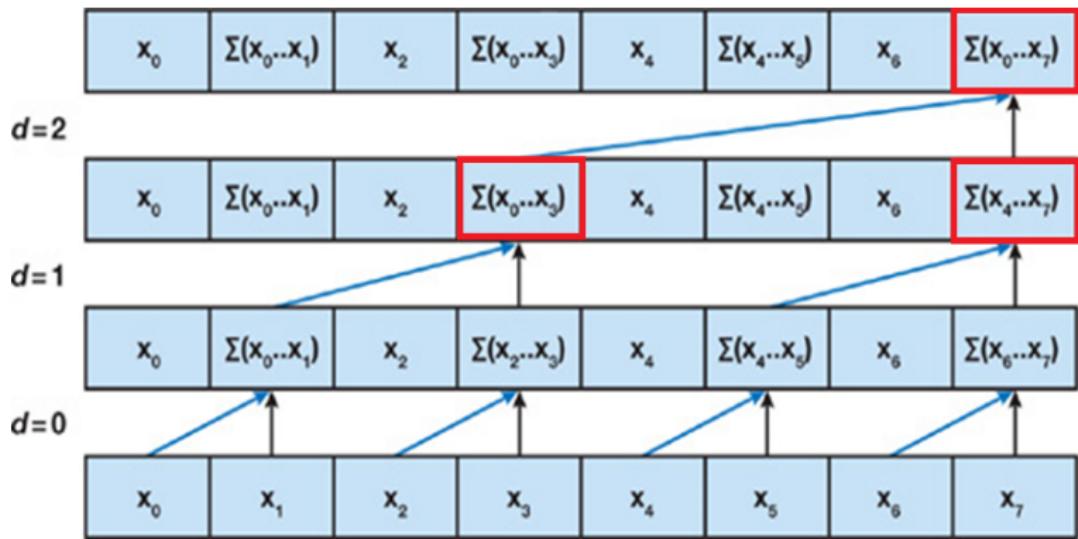
An illustration of the Up-Sweep phase



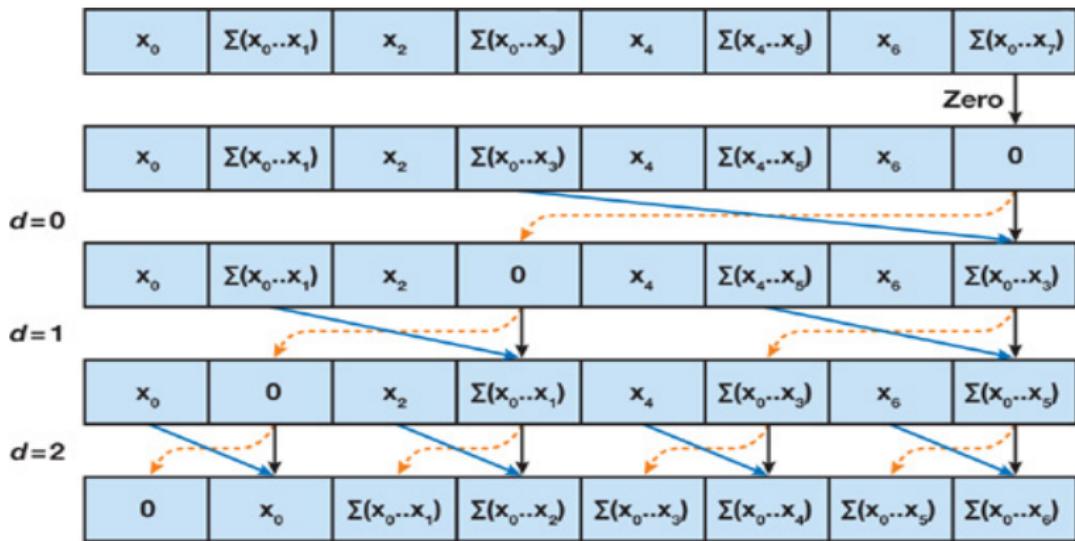
An illustration of the Up-Sweep phase



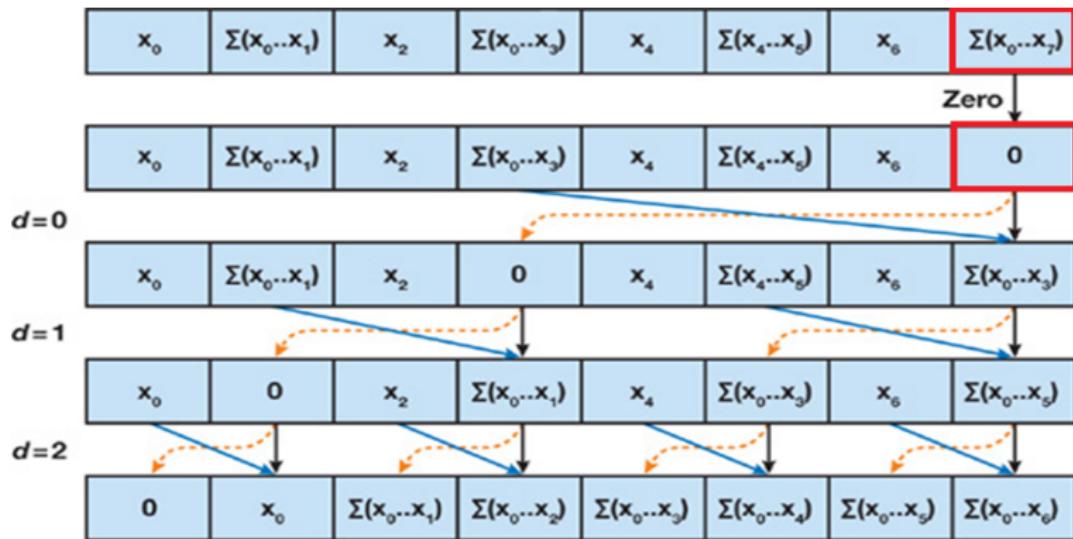
An illustration of the Up-Sweep phase



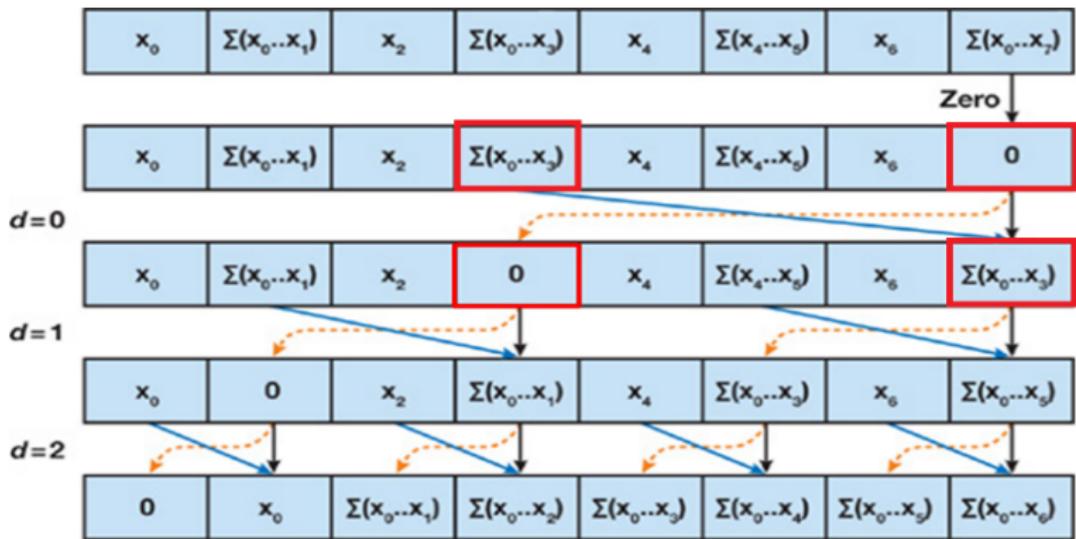
An illustration of the Down-Sweep phase



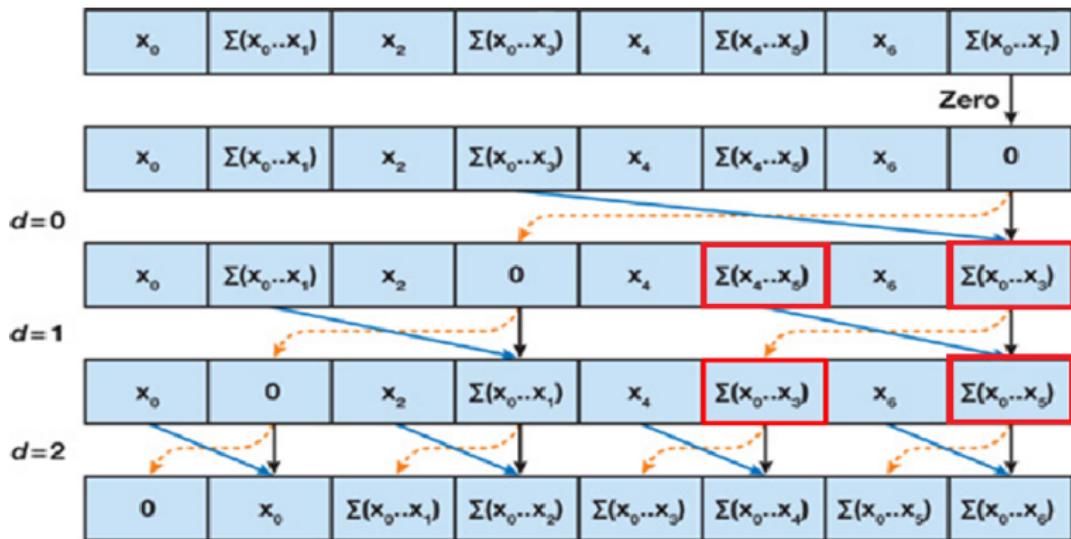
An illustration of the Down-Sweep phase



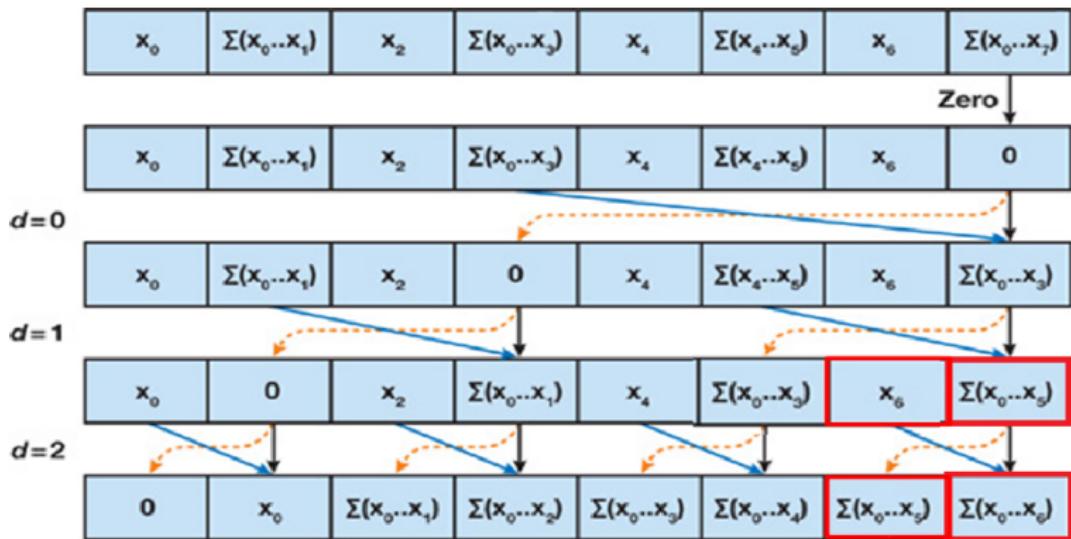
An illustration of the Down-Sweep phase



An illustration of the Down-Sweep phase



An illustration of the Down-Sweep phase



Complexity Analysis

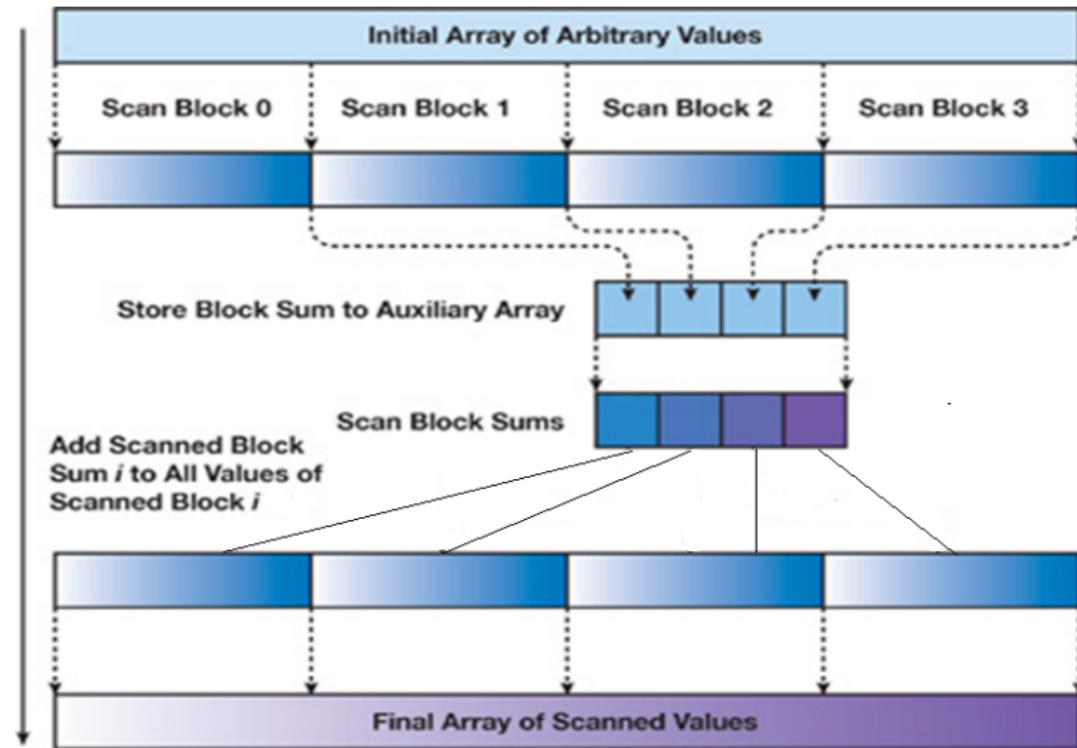
Up-Sweep Complexity:

- A binary tree with n leaves and $d = \log_2 n$ levels, and each level d has 2^d nodes. If it is performed one add per node, it is computed $O(n)$ adds on a single traversal of the tree.

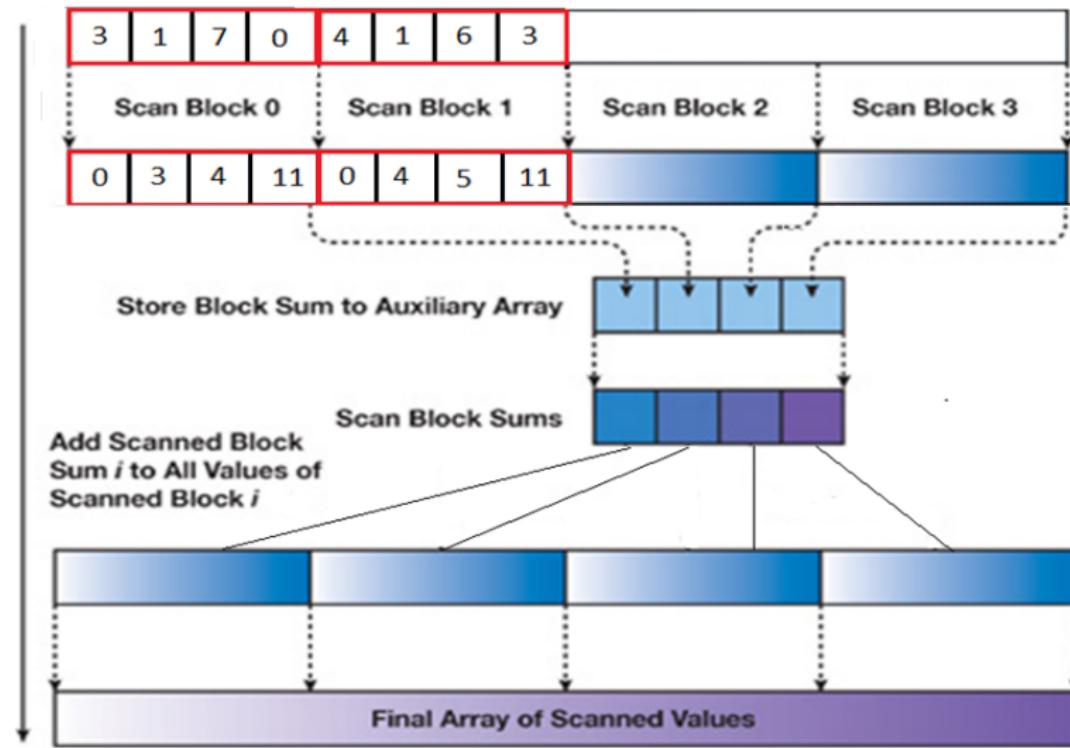
Down-Sweep Complexity:

- Similar as Up-Sweep phase. It is performed $O(n)$ adds and $O(n)$ swaps.

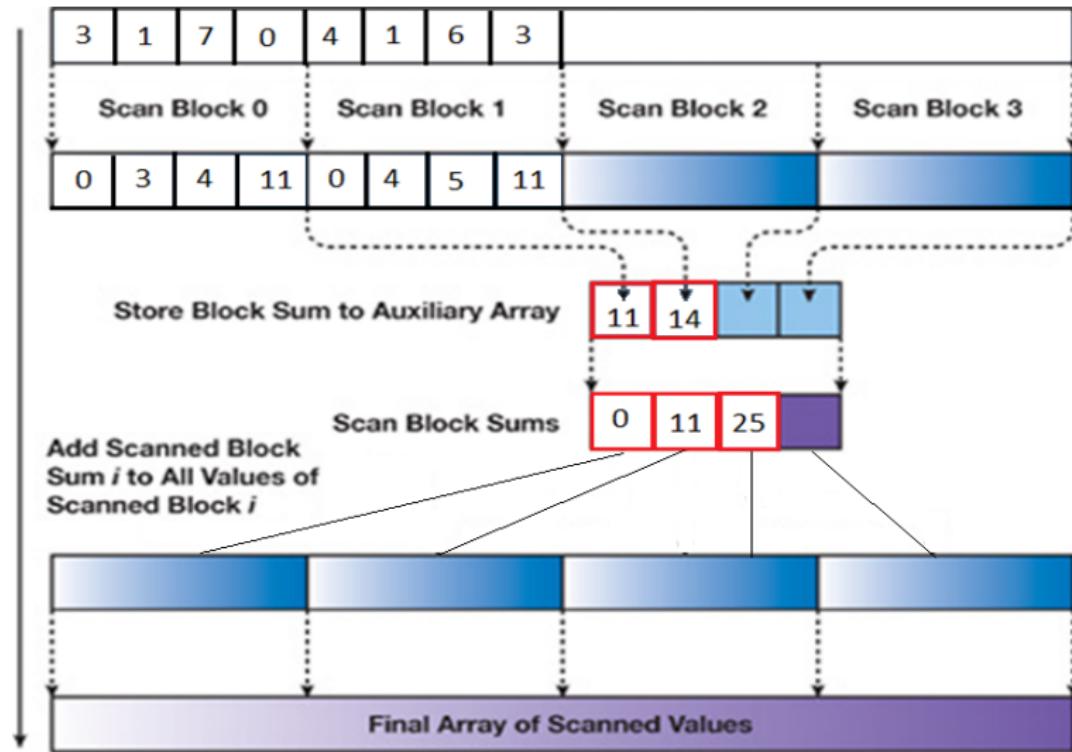
Algorithm for large arrays



Algorithm for large arrays



Algorithm for large arrays



Algorithm for large arrays

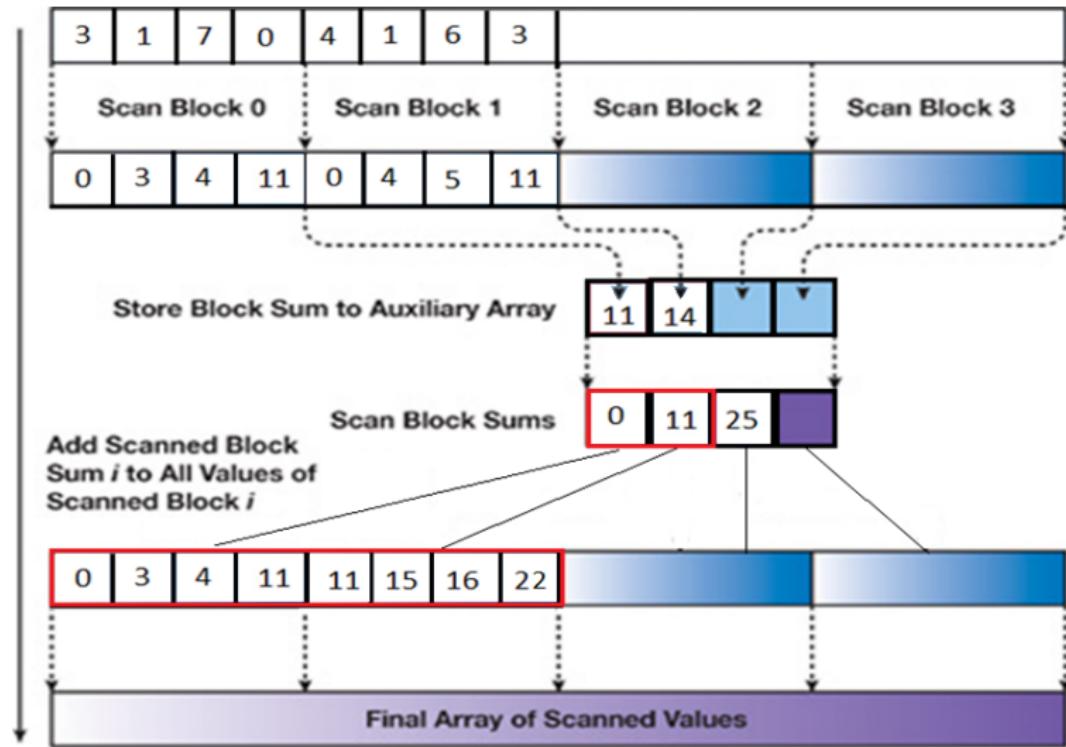


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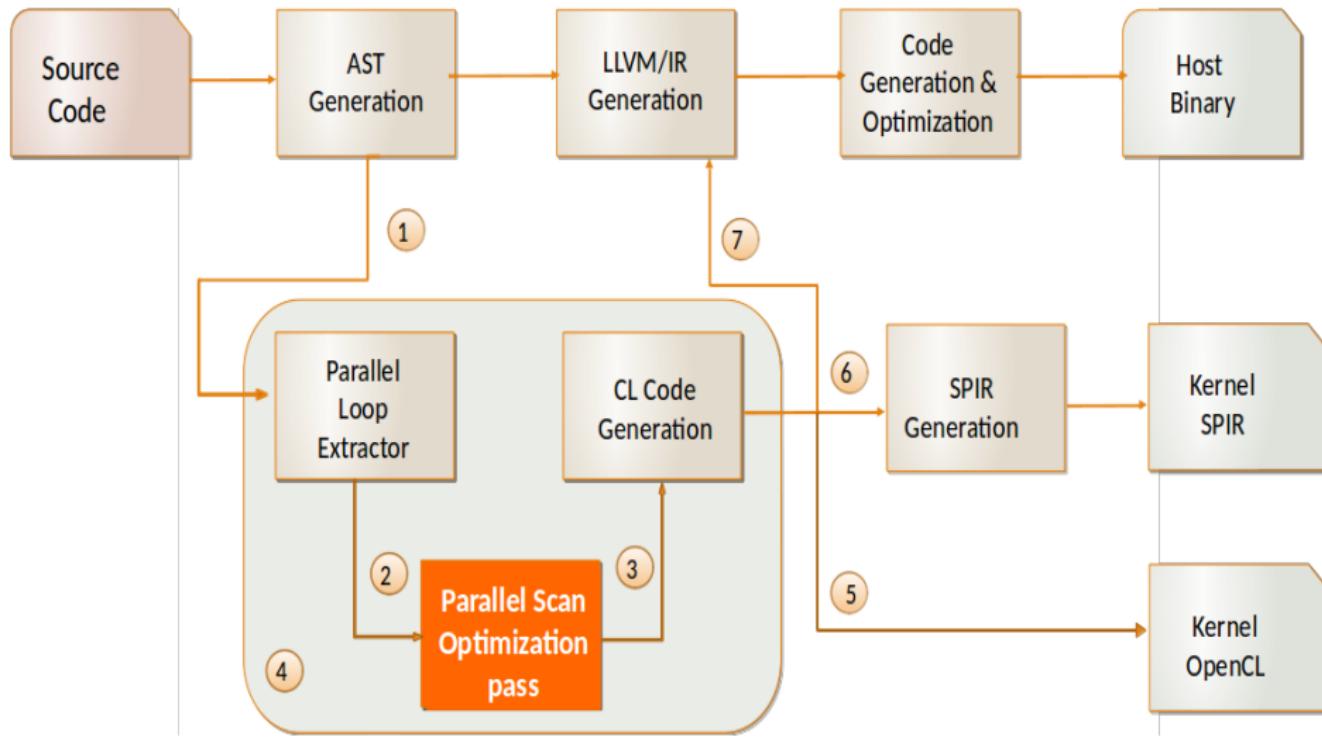
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What is AClang?



- AClang compiler is based in LLVM Clang 3.5;
- Designed by our group at UNICAMP;
- Supports Offloading to accelerators;
- From OMP to OpenCL or SPIR code.

AClang Compiler Pipeline



A Clang Compiler

Listing 1: Sequential Implementation of Scan

```
void scan(int *x, int *y, int n) {
    y[0] = 0;
    for(i = 1; i < n; i++)
        y[i] = y[i-1] + x[i-1];
}
```

Listing 2: Parallel implementation of Scan using the new clause

```
void scan(int *x, int *y, int n) {
    y[0] = 0;
    #pragma omp target device (device) \
                map(to:y[:N]) map(from:x[:N])
    #pragma omp parallel for scan (+:y)
    for(i = 1; i < n; i++)
        y[i] = y[i-1] + x[i-1];
}
```

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Implementation of Scan in AClang

The implementation is based on the best parallel scan algorithm known today (Mark Harris).

Main steps:

- The algorithm obtains the pieces of information of the `omp scan clause` (variable type, operator, vector size);
- Compute the number of blocks and threads per block to use (Scan algorithm just work for 2^k vector sizes);
- Generate code for the runtime library to call the OpenCL driver to compile the kernels and dispatch them for execution;
- Send information from `omp declare target section` (new variables types and operator overload).

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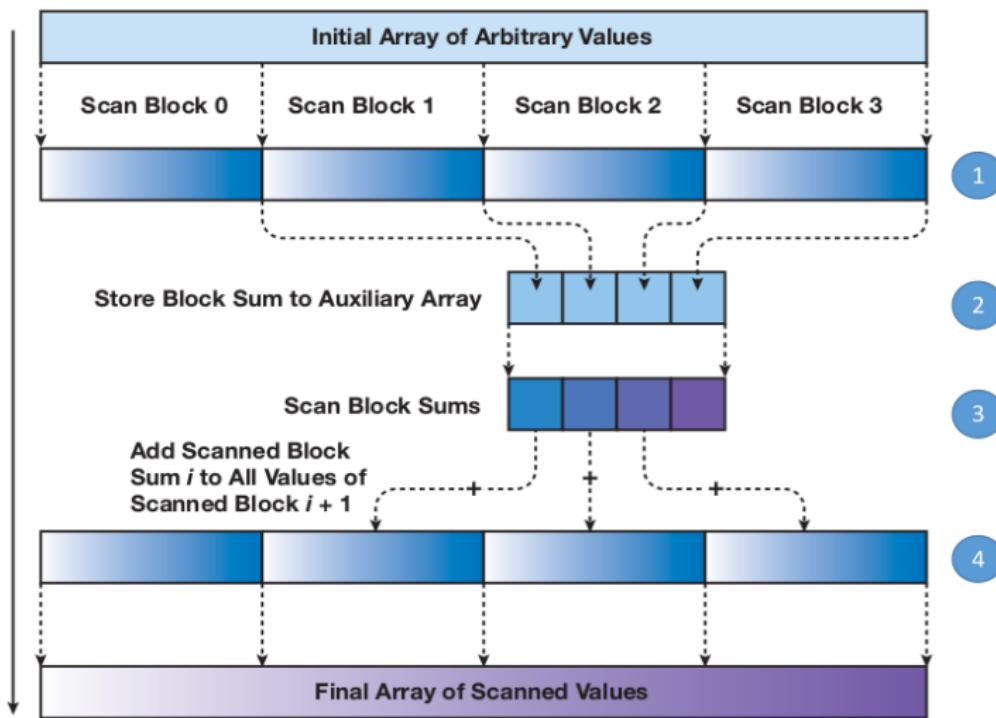
4 Using the Scan Operator

5 Experimental Evaluation

6 Conclusion and Future Works

The Template

The template represents the algorithm explained in the following figure:



Template's Structure

Listing 3: Template's Structure

```
//OMP_DECLARE_TARGET REGION
//END OMP_DECLARE_TARGET
#define Neutral I //Neutral value

__kernel void kernel_0 (datatype *input,\n
                      datatype *S, int n){\n
    //Performs (1) and (2)\n
}

__kernel void kernel_1(dataType *input, int n){\n
    //Performs (3)\n
}

__kernel void kernel_2(dataType *input,\n
                      dataType *output, dataType *S){\n
    //Performs (4)\n
}
```

The Template

The algorithm has only three parameters that could be different according to the applications.

- Variable type (int, float, double and so on);
- Operator used (+, *, &, |, *max*, *min* and so on);
- OMP declare target region (New variable type and operator).

The Template

Ouput and input vector are the same. In this case the last kernel does not have the output vector, the result is overwritten in input.

Listing 4: Return the result into the input vector

```
int main(){
    ...
    int aux1 = input[0], aux2;
    input[0] = 0;
#pragma omp target device (GPU) map(tofrom:input[:N])
    input[0] = 0;
#pragma omp parallel for scan(+:input)
    for(i = 0 ; i < n ; i++){
        aux2 = input[i];
        input[i] = input[i-1] + aux;
        aux = aux2;
    }
    ...
}

__kernel void kernel_2(dataType *input, dataType *S)
```

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Example of Applications

- Random number generation
- Sequence alignment
- N-body problem
- To perform lexical analysis
- Polynomial Evaluation
- To implement Parallel Quick Sort version
- Array Filter
- Solving linear recurrences

Example of Applications

- Random number generation
- Sequence alignment
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- Polynomial Evaluation
- To implement Parallel Quick Sort version
- **Array Filter**
- Solving linear recurrences

Example: Array Filter

Input: An array $A[l:r]$ of integers elements, and an element x from $A[l:r]$.

Output: Rearrange the elements of $A[l:r]$, such that for some index $k \in [l, r]$, all elements in $A[l:k]$ are smaller or equal than x and all elements in $A[k + 1:r]$ are larger than x .

A:

| | | | | | | | | | |
|---|---|---|----|---|---|---|----|---|----|
| 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 |
|---|---|---|----|---|---|---|----|---|----|

 $x = 8$

A:

| | | | | | | | | | |
|---|---|---|---|---|---|---|----|----|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 5 | 7 | 1 | 3 | 4 | 8 | 9 | 11 | 14 | 21 |

Example: Array Filter

A:

| | | | | | | | | | |
|---|---|---|----|---|---|---|----|---|----|
| 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 |
|---|---|---|----|---|---|---|----|---|----|

 $x = 8$

B:

| | | | | | | | | | |
|---|---|---|----|---|---|---|----|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 |

lt:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |

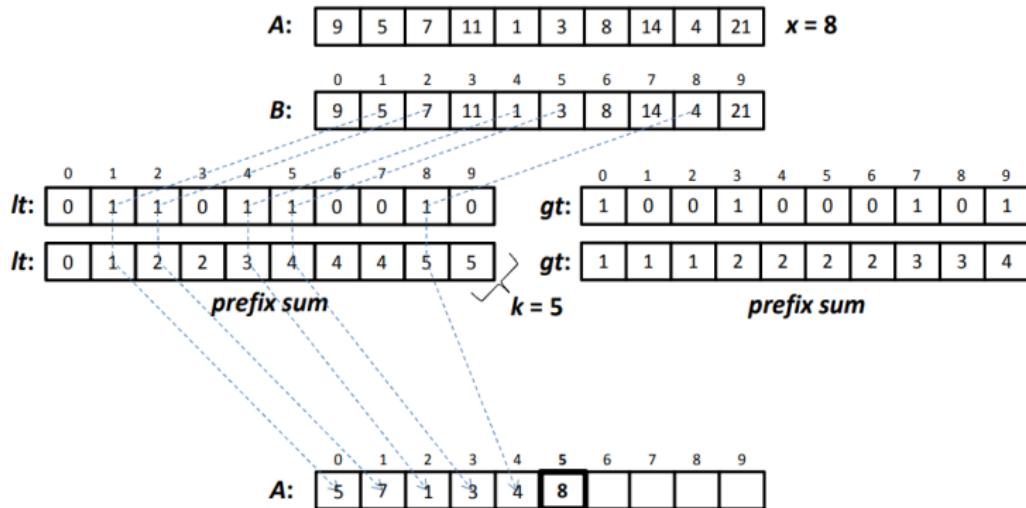
gt:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |

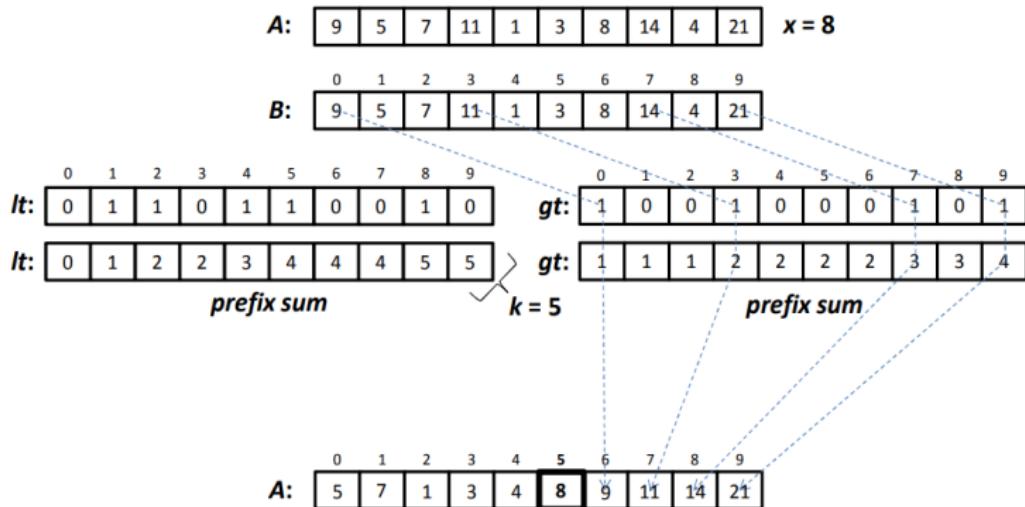
Example: Array Filter

| | | | | | | | | | | | | | | | | | | | | | | |
|-----|---|---|----|---|----|---|----|---|----|---|----|---|---|---|----|---|---|---|----|---|----|---|
| A: | <table border="1"><tr><td>9</td><td>5</td><td>7</td><td>11</td><td>1</td><td>3</td><td>8</td><td>14</td><td>4</td><td>21</td></tr></table> | 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 | $x = 8$ | | | | | | | | | | |
| 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 | | | | | | | | | | | | | |
| B: | <table border="1"><tr><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr><tr><td>9</td><td>5</td><td>7</td><td>11</td><td>1</td><td>3</td><td>8</td><td>14</td><td>4</td><td>21</td></tr></table> | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 | |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | | | | | | | | | | | | |
| 9 | 5 | 7 | 11 | 1 | 3 | 8 | 14 | 4 | 21 | | | | | | | | | | | | | |
| lt: | <table border="1"><tr><td>0</td><td>1</td><td>1</td><td>0</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td><td>0</td></tr></table> | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | $gt:$ <table border="1"><tr><td>1</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>1</td></tr></table> | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | | | | | | | | | | | | | |
| 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | | | | | | | | | | | | | |
| lt: | <table border="1"><tr><td>0</td><td>1</td><td>2</td><td>2</td><td>3</td><td>4</td><td>4</td><td>4</td><td>5</td><td>5</td></tr></table> | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 | 5 | $gt:$ <table border="1"><tr><td>1</td><td>1</td><td>1</td><td>2</td><td>2</td><td>2</td><td>2</td><td>3</td><td>3</td><td>4</td></tr></table> | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 4 |
| 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 | 5 | | | | | | | | | | | | | |
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | | | | | | | | | | | | | |

Example: Array Filter



Example: Array Filter



Source Code: Array Filter

Listing 5: Array Filter Implementation

```
int main(){
    int *A, *lt , *gt, ltScan, gtScan, x, N;
    Reading and allocating variables

    compute(lt, x, lower_equal); //In parallel
    compute(gt, x, greater);   //In parallel

    #pragma omp target device (GPU) map(to:ltScan[:N]) map(from:lt[:N])
    ltScan[0] = 0;
    #pragma omp parallel for scan(+:ltScan)
    for(i = 1 ; i < N ; i++)
        ltScan[i] = ltScan[i-1] + lt[i-1];

    #pragma omp target device (GPU) map(to:gtScan[:N]) map(from:gt[:N])
    gtScan[0] = 0;
    #pragma omp parallel for scan(+:gtScan)
    for(i = 1 ; i < N ; i++)
        gtScan[i] = gtScan[i-1] + gt[i-1];

    Rearrange the elements from A, using lt, gt, ltScan and gtScan //In parallel
}
```

Source Code: Array Filter

Listing 6: Array Filter Template Generated

```
#define Neutral 0

__kernel void kernel_0 (__global int *input,\n                      __global int *S, const int n)

__kernel void kernel_1 ( ... )

__kernel void kernel_2 ( ... )
```

Example of Applications

- Random number generation
- Sequence alignment
- N-body problem
- To perform lexical analysis
- Polynomial Evaluation
- To implement Parallel Quick Sort version
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A realistic Example: Fibonacci Series

Let

$$A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$$

And the Fibonacci numbers, defined by

$$F_0 = 0$$

$$F_1 = 1$$

$$F_{n+1} = F_n + F_{n-1}$$

Then by induction

$$A^1 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} F_2 & F_1 \\ F_1 & F_0 \end{bmatrix}$$

And if for n the formula is true, then:

$$A^{n+1} = A \cdot A^n = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} F_{n+1} & F_n \\ F_n & F_{n-1} \end{bmatrix}$$

$$A^{n+1} = \begin{bmatrix} F_{n+1} + F_n & F_n + F_{n-1} \\ F_{n+1} & F_n \end{bmatrix} = \begin{bmatrix} F_{n+2} & F_{n+1} \\ F_{n+1} & F_n \end{bmatrix}$$

Listing 7: Fibonacci Implementation

```
#pragma omp declare target
struct Matrix{
    long x00, x01, x10, x11;
    //Default constructor
    Matrix(){
        x00 = 1; x01 = 1;
        x10 = 1; x11 = 1;
    }
};

Matrix Operator *(Matrix A, Matrix C){
    return A*C;
}

#pragma omp declare target
```

Source Code : Fibonacci Series

Listing 8: Fibonacci Implementation

```
int main ( ) {
    Matrix *x = new Matrix[N];
    Matrix *y = new Matrix[N];
    ...
#pragma omp target device (GPU) \
            map (to: y[:N])  map (from: x[:N])
    y[0] = Identity_Matrix;
#pragma omp parallel for scan(*:y)
    for (i = 1; i < N; i++)
        y[i] = y[i - 1] * x[i - 1];
    ...
}
```

Source Code : Fibonacci Series

Listing 9: Fibonacci Template Generated

```
struct Matrix {
    long x00, x01, x10, x11;
};

Matrix *(Matrix A, Matrix C) {
    Mat X;
    X.x00 = A.x00 * C.x00 + A.x01 * C.x10;
    X.x01 = A.x00 * C.x01 + A.x01 * C.x11;
    X.x10 = A.x10 * C.x00 + A.x11 * C.x10;
    X.x11 = A.x10 * C.x01 + A.x11 * C.x11;
    return X;
}

#define Neutral (Matrix){ 1, 0, 0, 1 }

__kernel void kernel_0 (__global Matrix *input,
    __global Matrix *S, const int n)
__kernel void kernel_1 ( ... )
__kernel void kernel_2 ( ... )
```

Source Code : Fibonacci Series

Using Scan Clause

```
int main () {  
    Matrix *x = new Matrix[N];  
    Matrix *y = new Matrix[N];  
    ...  
#pragma omp target device (GPU) \  
map (tofrom: y[:N]) map (to: x[:N])  
#pragma omp parallel for scan (* : y)  
for (int i = 1; i < N; i++)  
    y[i] = y[i - 1] * x[i - 1];  
    ...  
}
```

main.c~30 lines

OpenCL direct Programming

```
#include "main.h"  
...  
int main () {  
    cl_int err = CL_SUCCESS;  
    cl_context context = clCreateContext(0, device_id, host_callbacks, host_error, host_info, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create OpenCL context!\n");  
    cl_command_queue queue = clCreateCommandQueue(context, 0, 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create command queue!\n");  
    cl_mem global_x = clCreateBuffer(context, CL_MEM_READ_WRITE, N * sizeof(float), 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create global memory for x!\n");  
    cl_mem global_y = clCreateBuffer(context, CL_MEM_READ_WRITE, N * sizeof(float), 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create global memory for y!\n");  
    cl_mem local_x = clCreateBuffer(context, CL_MEM_READ_WRITE, N * sizeof(float), 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create local memory for x!\n");  
    cl_mem local_y = clCreateBuffer(context, CL_MEM_READ_WRITE, N * sizeof(float), 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create local memory for y!\n");  
    cl_event event_x = clCreateEvent(context, 0, 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create event for x!\n");  
    cl_event event_y = clCreateEvent(context, 0, 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create event for y!\n");  
    cl_program program = clCreateProgramWithSource(context, 1, &kernel_code, 1, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create OpenCL program!\n");  
    cl_int err2 = clBuildProgram(program, 0, NULL, NULL, NULL, &err);  
    if (err2 != CL_SUCCESS)  
        printf("Error: Failed to build OpenCL program!\n");  
    cl_kernel kernel_x = clCreateKernel(program, "fibonacci_x", &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create kernel for x!\n");  
    cl_kernel kernel_y = clCreateKernel(program, "fibonacci_y", &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to create kernel for y!\n");  
    err = clSetKernelArg(kernel_x, 0, sizeof(cl_mem), &global_x);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for x!\n");  
    err = clSetKernelArg(kernel_x, 1, sizeof(cl_mem), &local_x);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for local_x!\n");  
    err = clSetKernelArg(kernel_x, 2, sizeof(cl_mem), &local_y);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for local_y!\n");  
    err = clSetKernelArg(kernel_x, 3, sizeof(cl_int), &N);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for N!\n");  
    err = clSetKernelArg(kernel_y, 0, sizeof(cl_mem), &global_y);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for y!\n");  
    err = clSetKernelArg(kernel_y, 1, sizeof(cl_mem), &local_y);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for local_y!\n");  
    err = clSetKernelArg(kernel_y, 2, sizeof(cl_int), &N);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to set kernel argument for N!\n");  
    err = clEnqueueNDRangeKernel(queue, kernel_x, 1, NULL, N, 1, 1, &event_x, 0);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to enqueue kernel x!\n");  
    err = clEnqueueNDRangeKernel(queue, kernel_y, 1, NULL, N, 1, 1, &event_y, 0);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to enqueue kernel y!\n");  
    err = clWaitForEvents(1, &event_x);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to wait for event x!\n");  
    err = clWaitForEvents(1, &event_y);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to wait for event y!\n");  
    err = clGetEventInfo(CL_EVENT_COMMAND_EXECUTION_STATUS, event_x, &status_x, 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to get event status x!\n");  
    err = clGetEventInfo(CL_EVENT_COMMAND_EXECUTION_STATUS, event_y, &status_y, 0, &err);  
    if (err != CL_SUCCESS)  
        printf("Error: Failed to get event status y!\n");  
    if (status_x == CL_COMPLETE && status_y == CL_COMPLETE)  
        printf("Success! Fibonacci series calculated!\n");  
    else  
        printf("Failure! Fibonacci series not calculated!\n");  
    clReleaseMemObject(global_x);  
    clReleaseMemObject(local_x);  
    clReleaseMemObject(local_y);  
    clReleaseMemObject(global_y);  
    clReleaseEvent(event_x);  
    clReleaseEvent(event_y);  
    clReleaseProgram(program);  
    clReleaseKernel(kernel_x);  
    clReleaseKernel(kernel_y);  
}
```

main.c~92 lines

kernel.cl~140 lines

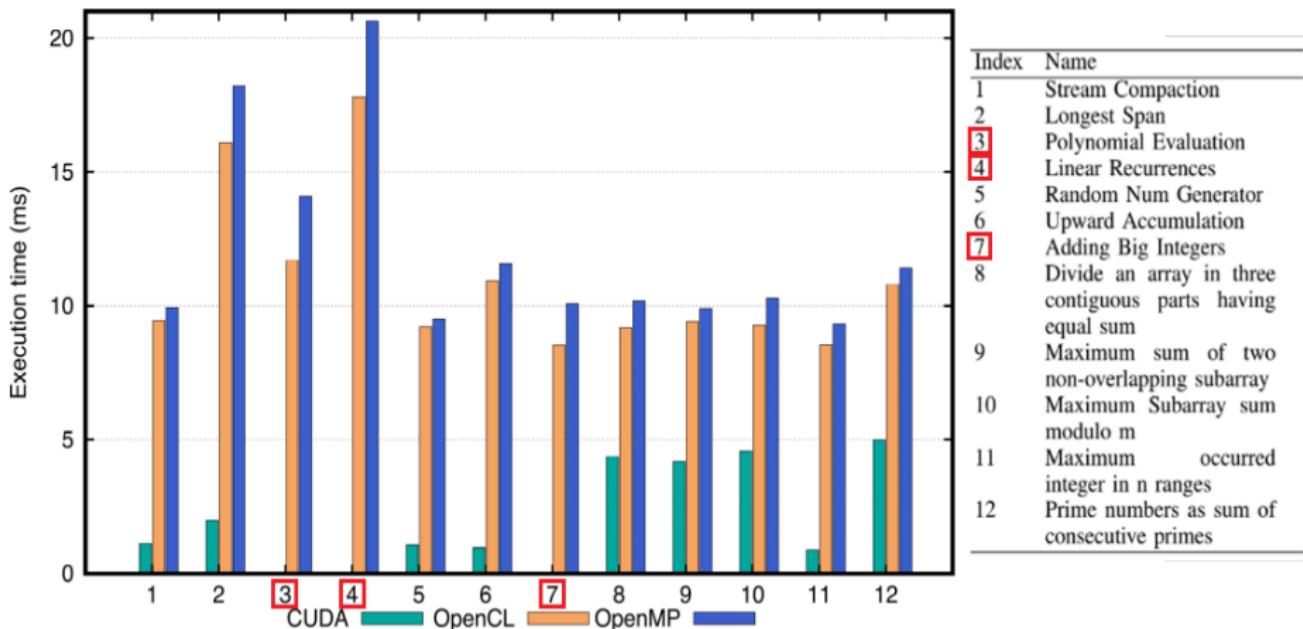
cl_functions.c~100 lines

Total ~ 332 lines

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- 4 Using the Scan Operator
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a) The execution on Intel Xeon CPU E5-2620 with NVIDIA Tesla K40c



b) The execution on Intel Core i5 with Intel Iris GPU

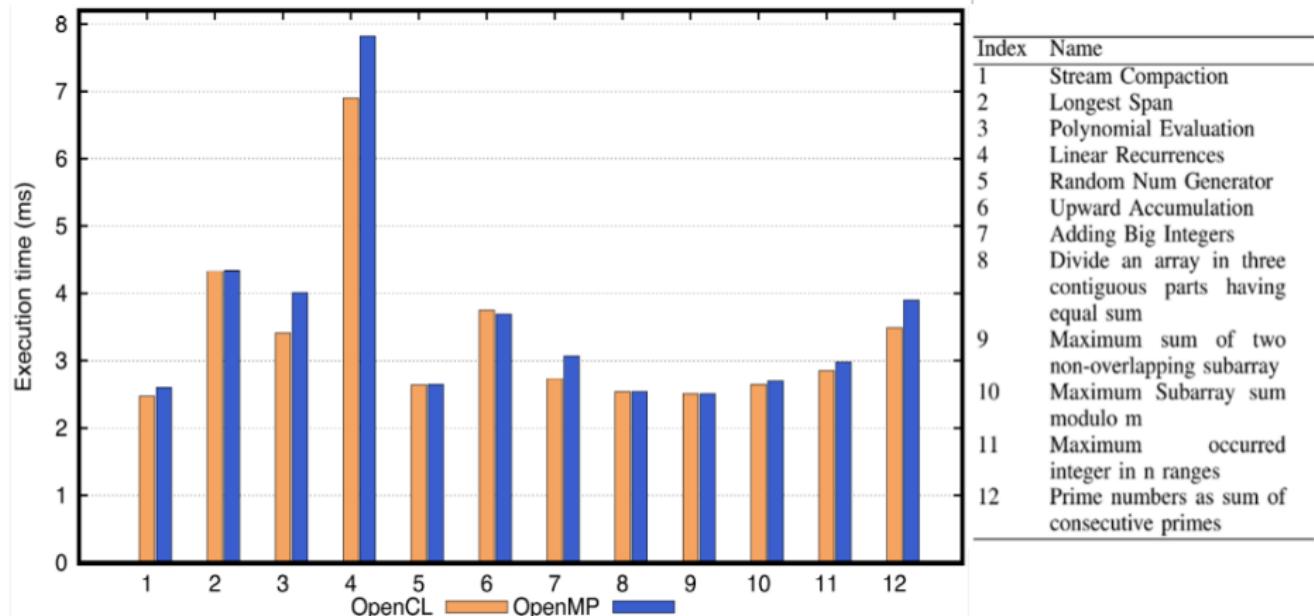


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Conclusion and Future Works

Conclusion:

- The scan operation is a simple and powerful parallel primitive with a broad range of applications;
- The new scan clause in OpenMP exhibits a similar performance as direct programming in OpenCL at a much smaller design effort.

Conclusion and Future Works

Future Works:

- Implement a template of scan algorithm for NVIDIA;
- Extend the limits of scan;
- Implement a template of reduction algorithm for AClang compiler;
- Improve the scan clause the performance by providing specific routines to handle scan operations into the AClang runtime library.

Thanks

THANKS!

