Automatic OpenCL Optimization for Locality and Parallelism Management

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Motivation

- **Tiling & fusion loops to improve locality**
  - For sequential loops:
    - If N > cache size, cache misses N times in the second loop;
    - If T < cache size, no cache miss in the second loop.

```
for(int i = 0; i < N; i++)
    A[i] = ...;
for(int j = 0; j < N; j++)
    ... = A[j];
```

```
parallel for(int t = 0; t*T < N; t++) {
        for(int i = t*T; i<min(N,(t+1)*T); i++)
            A[i] = ...;
        for(int j = t*T; j<min(N,(t+1)*T); j++)
            ... = A[j];
}
```

  - For OpenCL:

```
__kernel void f(__global char *A) {
    int i = get_global_id(0);
    A[i] = ...;
}
__kernel void g(__global char *A) {
    int j = get_global_id(0);
    ... = A[j];
}
```

```
parallel for(int i = 0 : N-1)
    A[i] = ...;
parallel for(int j = 0 : N-1)
    ... = A[j];
```

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Motivation

- **When inter-tile dependence exists:**
  - The transformation becomes illegal, unless introducing additional synchronization:

```
parallel for(int i = 0 : N-1)
    A[i] = ...;
parallel for(int j = 0 : N-1)
    ... = A[j-1] + A[j] + A[j+1];
```

```
parallel for(int t = 0 : N/T) {
    for(int i = t*T; i<min(N,(t+1)*T); i++)
        A[i] = ...;
    barrier(GLOBAL_MEM_FENCE);
    for(int j = t*T; j<min(N,(t+1)*T); j++)
        ... = A[j-1] + A[j] + A[j+1];
}
```

  - If we allow some redundant computation:

```
parallel for(int t = 0 : N/T) {
    __private a[t*T-1 : min(N,(t+1)*T)];
    for(int i=t*T-1;i<min(N,(t+1)*T)+1;i++)
        a[i] = ...;
    for(int j = t*T; j<min(N,(t+1)*T); j++)
        ... = a[j-1] + a[j] + a[j+1];
}
```

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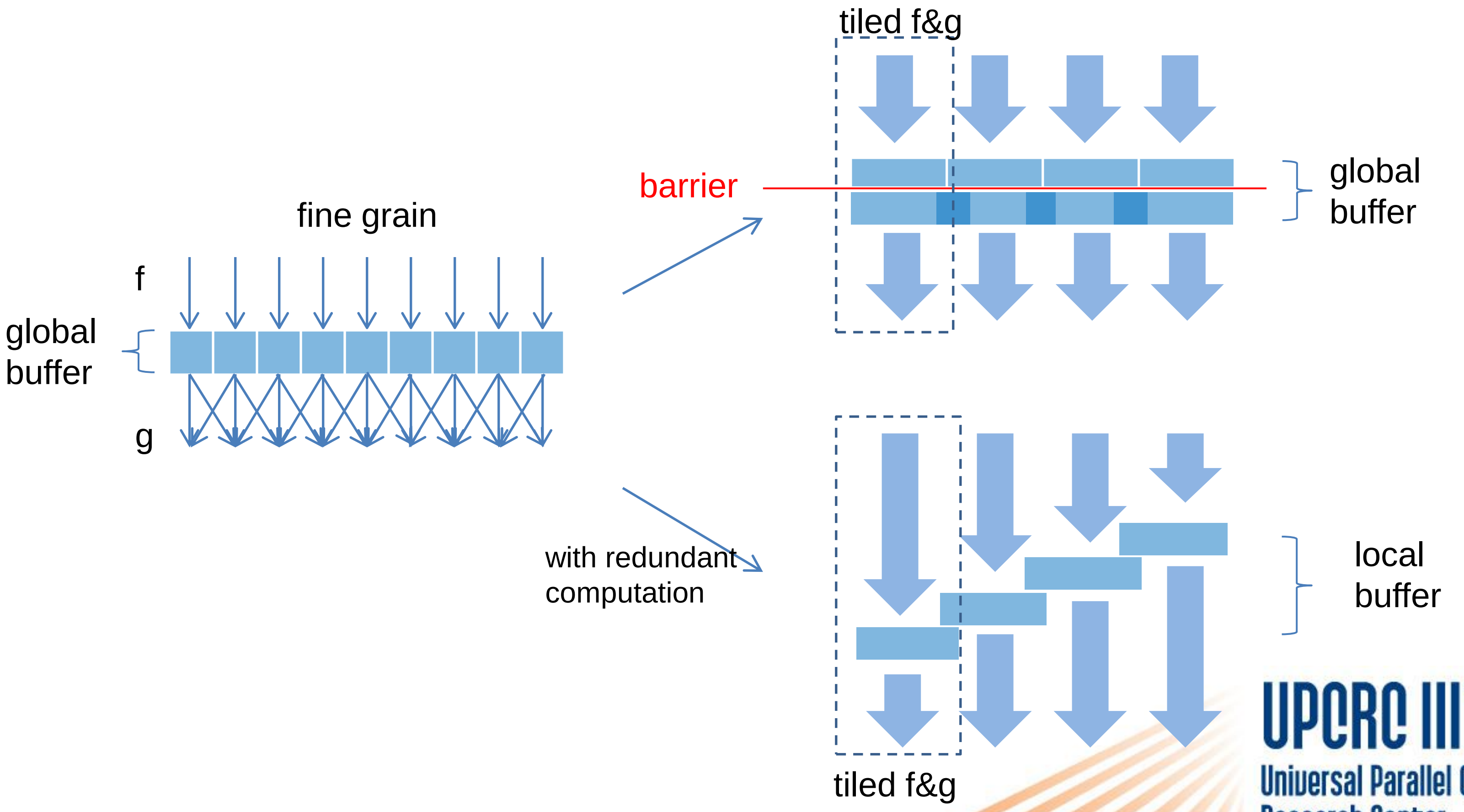
Motivation

- **Tile with redundant computation:**



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Across Kernel Boundaries

- **We need to optimize kernel code across kernel boundaries**

What the host code compiler (GCC) see:

```
clCreateProgramWithSource()
clBuildProgram()

clSetKernelArg(kernel_f, 0, sizeof(cl_mem), &mem_A);
clSetKernelArg(kernel_g, 0, sizeof(cl_mem), &mem_A);

size_t global_work_size[] = {N};
clEnqueueNDRangeKernel(queue, kernel_f, 1, NULL,
    global_work_size, NULL, 0, NULL, &event);
clEnqueueNDRangeKernel(queue, kernel_g, 1, NULL,
    global_work_size, NULL, 1, &event, NULL);
```

What the kernel code compiler see:

```
__kernel void f(__global char *A) {
    int i = get_global_id(0);
    A[i] = ...;
}
__kernel void g(__global char *A) {
    int j = get_global_id(0);
    ... = A[j] + A[j+1];
}
```

```
parallel for(int i = 0 : N-1)
    A[i] = ...;
parallel for(int j = 0 : N-1)
    ... = A[j] + A[j+1];
```

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Across Kernel Boundaries

- **Lazy compilation framework:**

What the host code compiler (GCC) see:

```
clCreateProgramWithSource()
clBuildProgram()
```

Save kernel source without compilation

```
clSetKernelArg(kernel_f, 0, sizeof(cl_mem), &mem_A);
clSetKernelArg(kernel_g, 0, sizeof(cl_mem), &mem_A);
```

Save kernel arguments

```
size_t global_work_size[] = {N};
```

Save work size

```
clEnqueueNDRangeKernel(queue, kernel_f, 1, NULL,
    global_work_size, NULL, 0, NULL, &event);
clEnqueueNDRangeKernel(queue, kernel_g, 1, NULL,
    global_work_size, NULL, 1, &event, NULL);
```

Save the event waiting relation between f and g

Finally, compiler the kernel code

```
parallel for(int i = 0 : N-1)
    A[i] = ...;
parallel for(int j = 0 : N-1)
    ... = A[j] + A[j+1];
```

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Our Approach

- **A OpenCL source to source compiler:**
  - Kernel code compiler only
  - Accept naive OpenCL kernel code containing fine-grain kernel functions as input
    - Typically each task (work item) contains the computation of a single data element in the output domain.
    - Use global buffers to pass data between kernel functions
  - Output transformed kernel source and supportive host code
  - Implemented as a pass in Cetus source to source compiler

Integer Tuple Space

- **Unified representation for iteration space and index space**
  - Omega Library provides a serial of manipulation routines
- **Integer tuple:**
  - a vector of integers; a point in space Z^d
  - x= $[x_0, x_1, ..., x_{d-1}]$
- **Integer tuple set:**
  - A set of integer tuples; described with constraints
  - $S = \{[0], [1], ..., [N-1]\} = \{[i] : 0 \leq i < N\}$
- **Integer tuple relation:**
  - A set-to-set mapping
  - $R = \{[k] \rightarrow [x] : k = x + 1\}$

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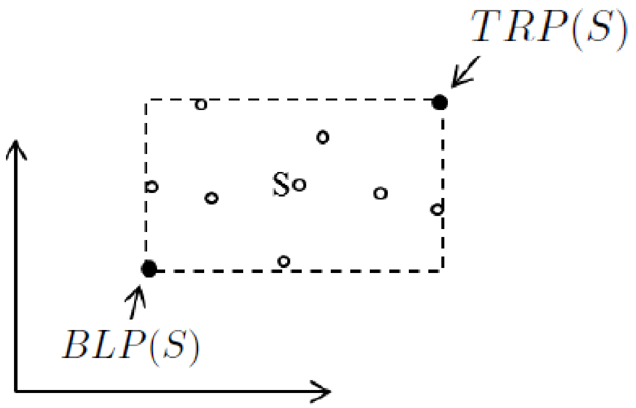
Integer Tuple Space

- $\in$, $\cup$, $\cap$, **operators are defined for integer tuples and sets**
- *minimum covering rectangle* **(MCR),** *bottom-left point* **(BLP) and** *top-right point* **(TRP) operators for integer tuple sets:**



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Kernel code analysis

- **What information do we need?**
  - Given a set of output elements, which kernel instances (tasks) can produce them?
    - index space (buffer array) → iteration space (implicit parallel loop)
  - Given a set of kernel instances, which input elements they need to consume?
    - iteration space → index space
- **Use two relations to represent the information above:**
  - Producing *relation*s:
    - For each array base with any write *set associated*, the *relation* from the **write index set** to the **work item id set**
  - Consuming *relation*s:
    - For each array base with any read *set associated*, the *relation* from the **work item set** to the **read index *set***

Kernel code analysis

- **Example: the producing and consuming *relations***

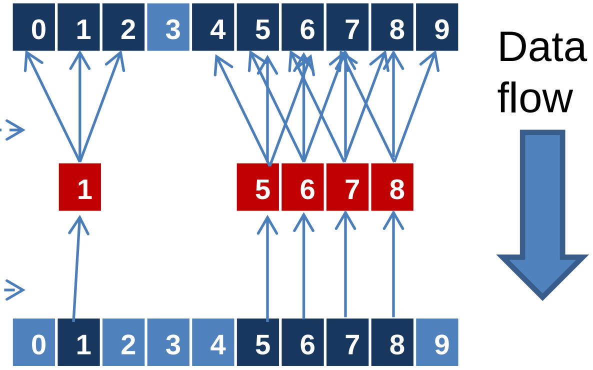
```
__kernel void g(__global char *A) {
    int j = get_global_id(0);
    ... = A[j-1] + A[j] + A[j+1];
}
```

- Consuming *relation* of array A:

  {[j]->[t]: j-1<=t<=j+1}

- Producing *relation* of array B:

  {[t]->[j]: t=j}



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Kernel code analysis

- **Example of the algorithm**

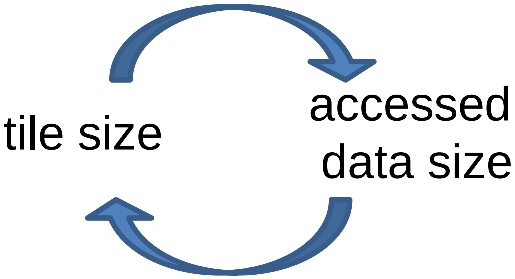
```
__kernel void g(__global char *A) {
    int j = get_global_id(0);
    ... = A[j-1] + A[j] + A[j+1];
}
```

- **The result consuming *relation* for array A is *R*:**

$$R1 = \{[id_0] \to [x_0] : x_0 = j - 1 \wedge j = id_0\}$$
$$R2 = \{[id_0] \to [x_0] : x_0 = j \wedge j = id_0\}$$
$$R3 = \{[id_0] \to [x_0] : x_0 = j + 1 \wedge j = id_0\}$$
$$R = R1 \cup R2 \cup R2 = \{[id_0] \to [x_0] : id_0 - 1 \leq x_0 \leq id_0 + 1\}$$

Tiling & fusion transformation

- **How to determine tile size?**
  - Goal: the data touched within a tile can fit local storage
  - Problem: the size of accessed data of different kernels are related to each other because of producing-consuming relation, and also related to the tile size



- **Solution: Symbolic tiling**
  - Assign symbolic boundaries for the tile
  - Build a data size function of the boundary symbols.
  - Search for the boundary symbol values with which the total data size can fit local storage

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Tiling & fusion transformation

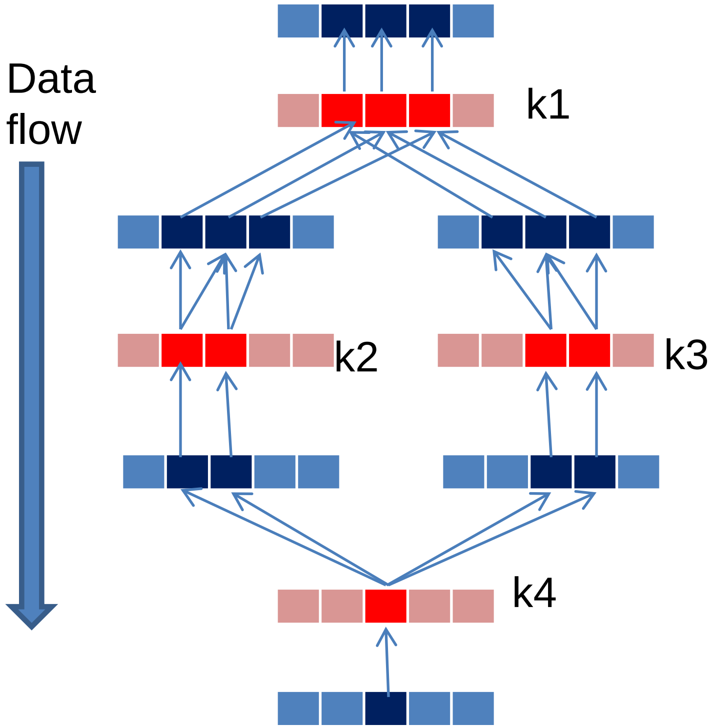
- **Algorithm of symbolic tiling:**

Input: $ConsumingRel[K]$ and $ProducingRel[K]$
for each kernel K
Output: $Tile[K]$ for each K
Initialization: $Tile[K] = \emptyset$, for each K

K_{start} = the last kernel in a topological order;
K_{end} = the last kernel in the same topological order;
$Tile[K_{start}] = \{[id_0, ..., id_{d-1}] : s_0 \leq id_0 < s_0 + len_0 \wedge$
$... \wedge s_{d-1} \leq id_{d-1} < s_{d-1} + len_{d-1}\}$;
for(each K in $K_{start}, .., K_{end}$ in reversed topological order) {
  $T = Tile[K]$;
  for(each array A that is an argument passed to K) {
    $C = ConsumingRel[K][A]$;
    $S = C(T)$;
    for(each kernel K_1 which is an ancestor of K in the DAG)
      if($ProducingRel[K_1][A]$!= null) {
        $P = ProducingRel[K_1][A]$;
        $T_1 = P(S)$;
        $Tile[K_1] = Tile[K_1] \cup T_1$;
      }
  }
}

Tiling & fusion transformation

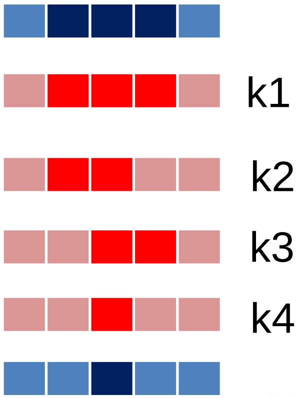
- **Algorithm of symbolic tiling:**



Topological order:
k1, k2, k3, k4

Processing order:
k4, k3, k2, k1

Fused kernel:



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Tiling & fusion transformation

- **Algorithm example:**
  - Kernel *g*'s consuming function:

    $$R = \{[id_0] \to [x_0] : id_0 - 1 \leq x_0 \leq id_0 + 1\}$$

  - Symbolic tile:

    $$Tile[g] = \{[id_0] : start_0 \leq id_0 < start_0 + len_0\}$$

  - Kernel *f*'s producing function:

    $$P = \{[x_0] \to [id_0] : x_0 = id_0\}$$

  - Calculate kernel *f*'s tile:

$$S = R(Tile[g]) = \{[x_0] : start_0 - 1 \leq x_0 < start_0 + len_0 + 1\}$$

$$Tile[f] = P(S) = \{[id_0] : start_0 - 1 \leq id_0 < start_0 + len_0 + 1\}$$

```
__kernel void f(__global char *A) {
    int i = get_global_id(0);
    A[i] = ...;
}
__kernel void g(__global char *A) {
    int j = get_global_id(0);
    ... = A[j-1] + A[j] + A[j+1];
}
```

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Tiling & fusion transformation

- **Search for the best tile size len :**
  - **Bound constraint**: tile size must be smaller than the global work size.
    - This constraint provides the lower and upper bound for the tile size search process.
  - **Parallelism constraint:** There must be enough tiles to keep the target device busy.
    - The constraint provides an upper bound for the value of len .
  - **Locality constraint:** The total size of all local buffers must fit in the local memory or cache
    - This constraint is another upper bound.

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Code Generation

- **Generate the fused kernel:**

```
__kernel void fused(__global char *A) {
    int gid_0 = get_global_id(0);
    int start_0 = gid_0 * len;
    __local a[len + 2];
    for(int i_0 = start_0 - 1; i_0 <
        start_0 + len + 1; i_0++)
        f(a, i_0);
    for(int i_0 = start_0; i_0 < start_0 +
        len; i_0++)
        g(a, i_0);
}
```

```
size_t global_work_size[] = {⌈N_0/len⌉, ⌈N_1/len⌉,
                             ..., ⌈N_{d-1}/len⌉};
clEnqueueNDRangeKernel(queue, kernel_fused, ...,
                       global_work_size, NULL, ...);
```

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Code Generation

- **Generate the fused kernel with parallelism recovery:**

```
__kernel void fused(__global char *A) {
    int lid_0 = get_local_id(0);
    int gid_0 = get_group_id(0);
    int start_0 = gid_0 * len;
    __local a[len + 2];
    int i_0 = lid_0 + start_0 - 1;
    if(i_0 >= start_0 - 1 && i_0 < start_0
        + len + 1)
        f(a, i_0);
    barrier(LOCAL_MEM_FENCE);
    i_0 = lid_0 + start_0;
    if(i_0>=start_0 && i_0<start_0+len)
        g(a, i_0);
}
```

```
size_t global_work_size[] = {⌈N_0/len⌉ * l_0,
           ⌈N_1/len⌉ * l_1, ..., ⌈N_{d-1}/len⌉ * l_{d-1}};
size_t local_work_size[] = {l_0, l_1, ..., l_{d-1}};
clEnqueueNDRangeKernel(queue,kernel_fused, ...,
       global_work_size, local_work_size, ...);
```

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Experiments

- **Platform:**

Mobile Platform	
CPU	**ATOM D525** Freq.: 1.8GHz; Number of cores: 2; Number of hw threads: 4; L1 data cache (per-core): 24KB; L2 cache (per-core): 512KB.
GPU	**NVIDIA ION** Number of multiprocessors: 2; Number of SPs: 16; Local memory size: 16KB; Global memory size: 511MB.
Workstation Platform[1]	
CPU	**Xeon L7555** Freq.: 1.87GHz; Number of processors: 4; Number of cores: 32; Number of hw threads: 32 (SMT disabled) L1 data cache (per-core): 32KB; L2 cache (per-core): 256KB; L3 cache (per-processor): 24MB.
GPU	**GeForce GTX 480** Number of multiprocessors: 15; Number of SPs: 480; Local memory size: 48KB; Global memory size: 1535MB.

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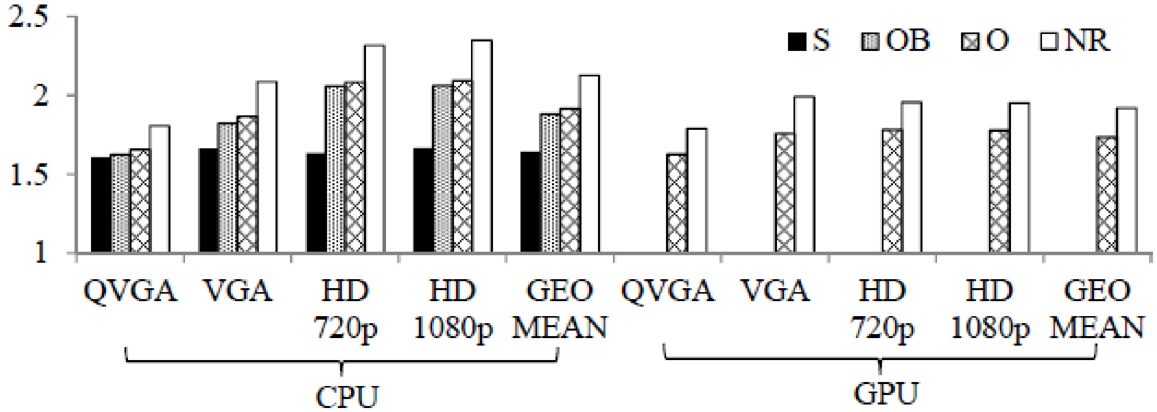
Experiments

- **Mobile platform**
  - Video post-processing application (VPP) with 3 video post processing filters: *StrongPostFilter*, *DenoiseDegrain* and *IppSharp*.



- **S** : Simple tiling and fusion with global barriers
- **OB**: Tiling & fusion with redundant computation, and with global barriers
- **O**: The optimized code (tiling & fusion with redundant computation)
- **NR**: Tiling & fusion WITHOUT redundant computation
  (cannot produce correct result)

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Experiments

- **Workstation platform:**
  - 4 iterative stencil loop applications

	Jacobi	PathFinder	HotSpot	Cell
Dimension of data	1	1	2	3
Input size	64K	100K	512x512	60x60x60

```
while (some_condition) {
    clSetKernelArg(kernel, 0, input);
    clSetKernelArg(kernel, 1, output);
    clEnqueueNDRangeKernel(kernel, …);
    tmp = input;
    input = output;
    output = tmp;
}
```

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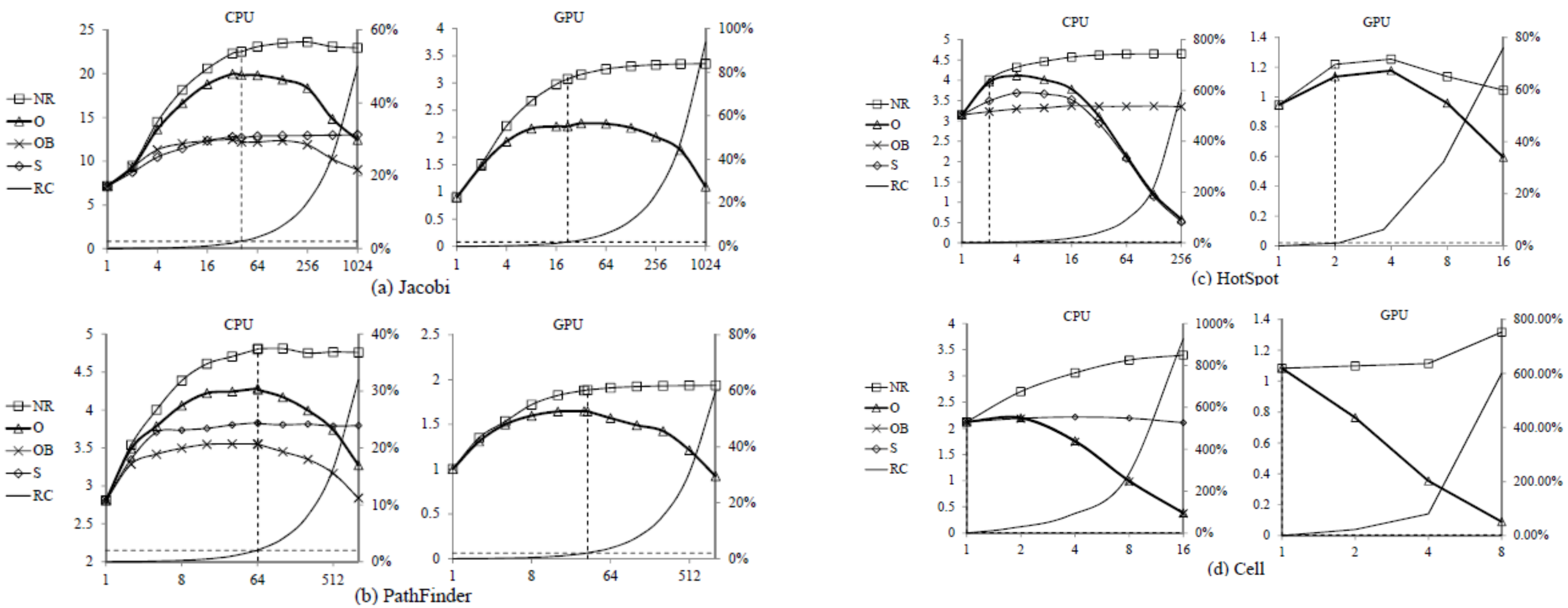
Experiments

- **Workstation platform:**
  - RC: the percentage of redundant computation introduced



Conclusion

- Machine-independent memory hierarchy optimization and work item organization for OpenCL programs.
- A lazy compilation framework which makes global optimizations across kernel boundaries possible.
- Tiling & fusion transformation with redundant computation to eliminate synchronizations.

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The End

- **Questions?**