Work Stealing Scheduler for Automatic Parallelization in FAUST

Linux Audio Conference

S. Letz, Y. Orlarey, D. Fober

GRAME
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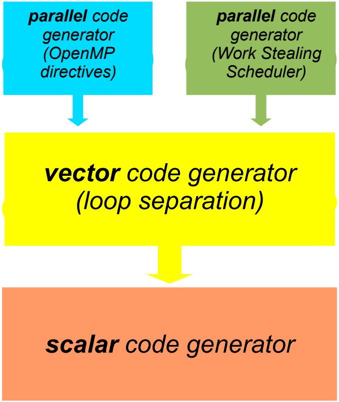
Outline

1. Work Stealing Scheduler

2. Demo

FAUST compilation stack

New Work Stealing Scheduler



FAUST compilation stack

How is the code generated?

- Scalar code is compiled as a unique big loop
- Vectorized code is compiled as separated smaller loops communicating with vectors
- Parallel code executes the graph of loops (= tasks) in parallel

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Parallelizing the DAG

The computation DAG

- Tasks are organized as a Direct Acyclic Graph
- The graph is executed on a "vector size" that can be less or equal to callback buffer size
- Input buffers are consumed and output buffers are produced

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Using OpenMP

- The DAG is sorted to express a sequence of parallel group of tasks
- OpenMP pragmas are then added at appropriate location
- Synchronization points between parallel sections

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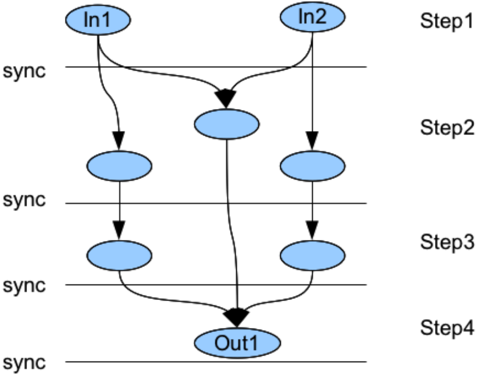

Parallelizing the DAG

```
#pragma omp parallel
for (int index = 0; index < fullcount; index += 32) {
    int count = min (32, fullcount-index);
    FAUSTFLOAT* input0 = &input[0][index];
    FAUSTFLOAT* input1 = &input[1][index];
    FAUSTFLOAT* output0 = &output[0][index];
    FAUSTFLOAT* output1 = &output[1][index];


    // SECTION : 1
    #pragma omp sections
    {
        #pragma omp section
        {
            // DSP code
        }
        #pragma omp section
        {
            // DSP code
        }
    }

    // SECTION : 2
    #pragma omp sections
    {
        #pragma omp section
        {
            // DSP code
        }
        #pragma omp section
        {
            // DSP code
        }
        #pragma omp section
        {
            // DSP code
        }
    }

    // SECTION : 3
    #pragma omp sections
    {
        #pragma omp section
        {
            // DSP code
        }
        #pragma omp section
        {
            // DSP code
        }
    }

    // SECTION : 4
    #pragma omp single
    {
        // DSP code
    }

}
```

Parallelizing the DAG

OpenMP performances

- Works quite well with Intel icc compiler
- But not so well with gcc... (even not at all on OSX)
- Expressed parallelism is not optimal (too much synchronization points...)

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Explicit graph scheduling

Data-flow model

- Input tasks are ready to be executed
- Activations go from input to output following data dependencies links
- A given task can be executed when it's inputs have been executed
- We want to minimize the global execution time

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Static versus dynamic graph scheduling

Scheduling models

- A lot has been written on the subject
- Basically two different approaches:
- - static scheduling: finding a "mapping" of tasks on the set of cores before actual execution
- - dynamic scheduling: doing the "mapping" at runtime

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Dynamic model

- Choice of task execution done at runtime
- A set of worker threads to execute tasks
- Worker threads have to find ready tasks, execute them and propagate "activations"

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- One global shared queue of "ready" tasks
- When a task is executed, possibly push ready output tasks in the queue
- All idle threads try to Pop ready tasks from the queue
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Principle

- A well known algorithm used for instance in Cilk++ (an extension to C/C++ for multithreaded parallel programs)
- Aims at improving the simple model previously described
- Has some interesting properties useful for fined-grained parallelism

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Work Stealing Scheduler (2)

Operations

- One queue by thread (considered as "private")
- The Work Stealing Queue has a "private" Push, LIFO Pop and a "public" FIFO Pop operations
- Each thread push ready tasks in it's private queue
- It get ready tasks from it's private queue until empty
- It can then "steal" tasks from other threads using their FIFO Pop operation

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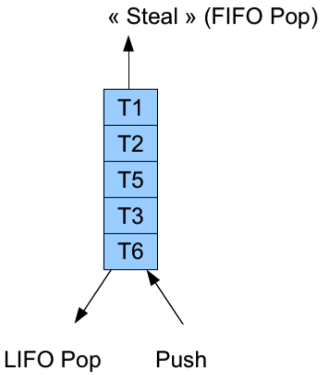
Work Stealing Queue

Operations on the WSQ



Work Stealing Scheduler (3)

Properties

- Less contention since each thread has its own queue
- Each thread can follow a "computation path" until its end, improving cache behaviour
- The "stolen" tasks are the ones pushed first, they are "near the inputs", thus they usually correspond to longer computation path

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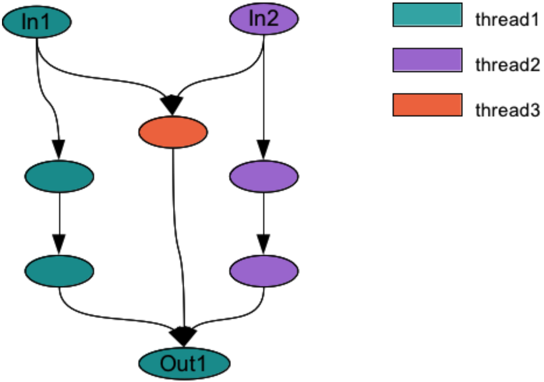

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Why?

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- For each task after DSP computation, the code to propagate activations only depends of the graph topology

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ComputeThread method

- Tasks are numbered
- For a given task, its "activation" value (number of inputs) is prepared
- The DAG is compiled as a big switch/case block to be executed by each thread
- Each sub-block contains the actual DSP code and the "propagate activations" code
- Two additional tasks are added: a "work stealing" task and an "end task"
- Before entering the switch/case block, ready input tasks are distributed among worker threads

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ComputeThread method

```
void computeThread(int cur_thread) {
{
    TaskQueue taskqueue(cur_thread);
    int tasknum = -1;
    int count = fFullCount;
    // Init input and output
    FAUSTFLOAT* output0 = &output[0][fIndex];
    FAUSTFLOAT* output1 = &output[1][fIndex];
    int task_list_size = 2;
    int task_list[2] = {2,3};
    taskqueue.InitTaskList(task_list_size, task_list, fDynamicNumThreads, cur_thread, tasknum);
    while (!fIsFinished) {
        switch (tasknum) {

            case 2: {
                // TASK code
            }
            case 3: {
                // TASK code
            }
            ....
        }
    }
}
```

Compilation of the Work Stealing Scheduler (3)

Activation code for each connection type

- When possible a task is chosen at the "direct" output
- Ready tasks are Pushed into private WSQ
- Atomic decrement the activation counter of output tasks with several inputs (possibly getting one to execute...)
- Otherwise WORK_STEALING_INDEX is returned and Work Stealing task will be executed

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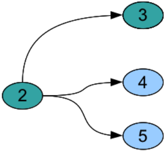
Compiling tasks activation code

Several outputs tasks (without other inputs)



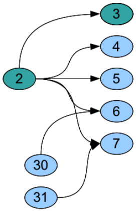

```
case 2: {

    // DSP code

    // Output tasks activation code
    taskqueue.PushHead(4);
    taskqueue.PushHead(5);
    tasknum = 3;
    break;
}
```

Compiling tasks activation code

Several outputs tasks (some without other inputs, some with other inputs)

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case 2: {

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    fGraph.ActivateOutputTask(taskqueue, 6);
    fGraph.ActivateOutputTask(taskqueue, 7);
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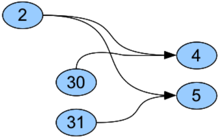


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    tasknum = WORK_STEALING_INDEX;
    fGraph.ActivateOutputTask(taskqueue, 4, tasknum);
    fGraph.ActivateOutputTask(taskqueue, 5, tasknum);
    fGraph.GetReadyTask(taskqueue, tasknum);
    break;
}
```

Compilation of the Work Stealing Scheduler (4)

Special tasks

- Work Stealing task aims to find a ready task in other threads (possibly "busy-looping")
- All output of the DAG are connected to the "end task"
- When executed, end task returns from the thread

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- When executed, end task returns from the thread

Special tasks

Work stealing and end tasks

```
case WORK_STEALING_INDEX: {
    tasknum = TaskQueue::GetNextTask(cur_thread, fDynamicNumThreads);
    break;
}

case LAST_TASK_INDEX: {
    fIsFinished = true;
    break;
}
```

Compilation of the Work Stealing Scheduler (5)

Compute method

- Called by "master thread"
- Init graph state (activations)
- Wakes up worker threads, also participates
- After computation, synchronization code to wait for all worker threads to finish

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Compute method

Called by "master " thread

```
virtual void compute (int fullcount, FAUSTFLOAT** input, FAUSTFLOAT** output) {
    this->input = input;
    this->output = output;
    for (fIndex = 0; fIndex < fullcount; fIndex += 32) {
        fFullCount = min (32, fullcount-fIndex);
        TaskQueue::Init();
        // Initialize end task, if more than one input
        fGraph.InitTask(1,2);
        // Only initialize taks with more than one input
        fGraph.InitTask(19,8);
        fGraph.InitTask(20,8);
        fIsFinished = false;
        fThreadPool->SignalAll(fDynamicNumThreads - 1, this);
        computeThread(0);
        while (!fThreadPool->IsFinished()) {}
    }
}
```

Init method

- Creates worker threads, put them in sleep mode
- Worker threads will inherit "compute method" thread scheduling properties and priorities

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More parallelism (1)?

Pipelining

- Some graph are sequential by nature
- Pipelining idea : duplicating each task several times
- Connecting with the appropriate outputs
- Each "sub-task" to be run on a slice of the buffer
- Recursive and non-recursive tasks are treated differently
- Still to be tested...

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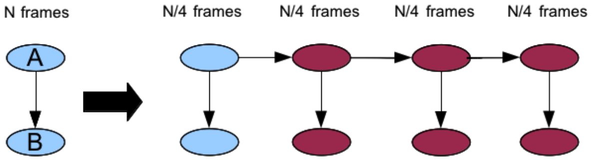
Pipeling the graph

Example of graph rewriting



More parallelism (2)?

Bottleneck-task duplication ?

- Some tasks have "bottleneck" behaviour
- Could be interesting to just duplicate them, (executing them several times in different threads...)
- Less synchronization points, thus better global results
- Need to find a proper a method to find out those tasks
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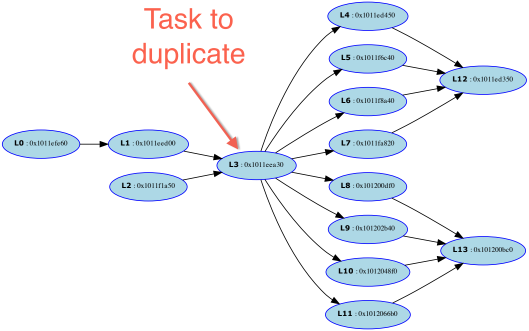
Bottleneck task duplication

Example of Karplus8 graph



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Finding where time is spent

- Estimating "busy-loop" cost (in the order of 30-50 usec on Sampo Combo organ run with 4 threads)
- Possibly yiedling if waiting for too long (with a configurable parameter, similar to icc OpenMP KMP_BLOCKTIME)
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- Usually do not benefit from parallelization or marginally
- See Yann workshop from yesterday...

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WSS versus OpenMP

- Comparable with icc OpenMP, even better in some cases
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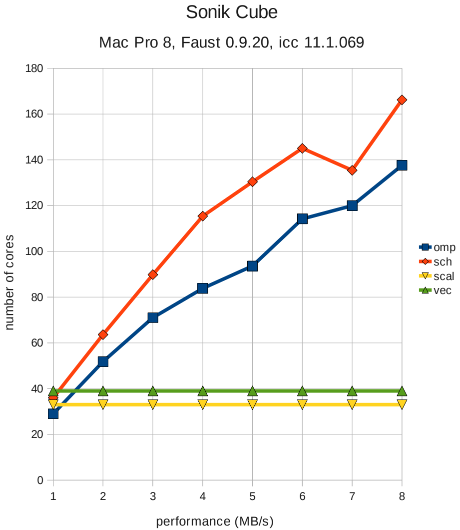
Sonik Cube


Sonik Cube
Mac Pro 8, Faust 0.9.20, icc 11.1.069
number of cores
performance (MB/s)
0
20
40
60
80
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120
140
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1
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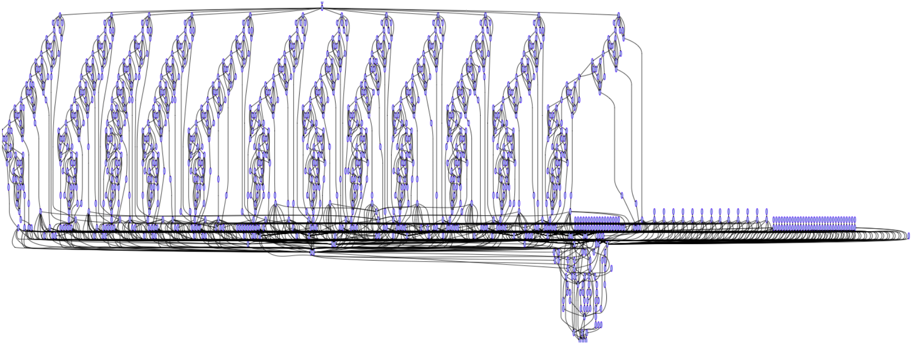
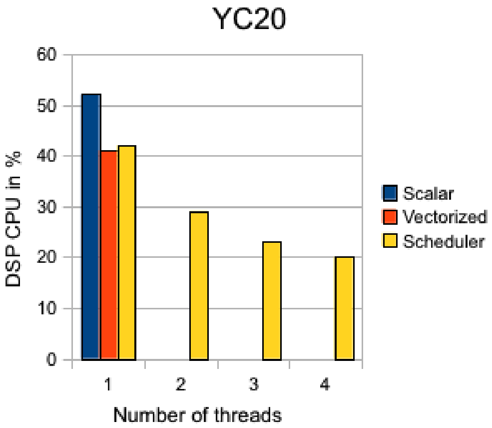
YC20

Graph of 991 tasks...



At 128 frames, 48 kHz with JACK : with 4 threads, 2 times faster than vectorized mode, 2.5 faster than scalar mode



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Limits of the current approach

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Some idea of solutions

- Re-organising the task code in separated methods helps compilers
- Still need to improve task code sharing...
- Using threading libraries like "libdispatch" (part of OSX Grand Central Dispatch), but not yet adapted for RT fined grained code
- Using inter-process audio frameworks (like JACK...) to share context between audio RT applications (like for instance the adequate RT threads number to be used, depending of graph topology...)
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Outline

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2. Demo