KART – Kernel compilation At RunTime for Improving HPC Application Performance

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Problem

Information that could dramatically improve compiler optimisation, i.e. application runtime, is not available at compile-time.

Motivation

Real-World Example . . .

- . . . from porting an OpenCL kernel to OpenMP
- SIMD vectorisation ⇒ AoSoA memory layout ⇒ complex index computations

```
    // in a loop nest:  group_id (parallel), local_id (simd), i, j, k
sigma_out[group_id * VEC_LENGTH * 2 * DIM * DIM + 2 * VEC_LENGTH *
    (DIM * i + j) + local_id]
```

- without the input runtime-constant `DIM` the compiler does not recognise the contiguous memory accesses pattern ⇒ gather/scatter SIMD loads/stores
- defining `DIM` at compile-time yields contiguous loads/stores ⇒ up to **2.6x**

Problem

Information that could dramatically improve compiler optimisation, i.e. application runtime, is not available at compile-time.

- dependant on **runtime constants**
  - ⇒ e.g. input data, number of nodes in a job, partitioning, data layouts, etc.

⇒ conditional elimination, loop transformation, memory access optimisation, . . .

⇒ **enable/improve SIMD vectorisation**

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Solutions?

a) at application compile time
   - recompile code for a specific runtime scenario (input)
   - pre-generate code versions for a possible parameter space

b) **defer compilation of kernels (i.e. hotspots) until application runtime**
   - OpenCL does that by design (for hardware portability)
   - CUDA since recently via NVRTC extension
   - **OpenMP** (and others) **cannot**

Design Space

A. Recompile Everything

- process input somehow at build time
- use data for compilation

✓ no runtime compilation complexity

✓ cross module optimisation

× recompilation of non hot-spots

× large time overhead for large codes

× input-data needs to be processed at build time

  ⇒ typically a task of the compiled code

× no binary releases

Design Space

B. Pre-instantiate Code for all Cases

- generate code variants for sets of relevant parameters and **select at runtime**
  - e.g. template value-parameter specialisation
- fall-back default implementation
- performed by some compilers
  - e.g. vectorised (masked/unmasked, . . .) and non-vectorised loop/function versions

✓ no runtime compilation complexity

✓ uses application code for input processing

× limited to small, discrete parameter domains

× limited to a small number of such parameters

× increased size of generated code

Design Space

C. Call a Compiler Library at Runtime

- compile hotspot code at runtime using a suitable library
  - OpenCL (intended for portability, own kernel language and runtime)
  - LLVM

✓ uses application code for input processing

✓ not limited by number of parameters/domains

× runtime overhead for compilation

× limited to the capabilities of the chosen library (i.e. LLVM)

- LLVM lacks SIMD math functions

× porting to OpenCL is a major effort

Design Space

D. Call an Arbitrary Compiler at Runtime

- call a command line toolset
  - GCC, Clang/LLVM, Intel, Cray, ...
- create and load shared library

✓ uses application code for input processing

✓ not limited by number of parameters/domains

✓ use capabilities of any command line toolset

× larger runtime overhead for compilation

⇒ **model of choice**

KART

Library: **KART** - **K**ernel-compilation **A**t **R**un**T**ime

- provide means for runtime compilation and invocation of arbitrary functions
- API for **C, C++**, and **Fortran** (implemented in modern C++)
- API similar to OpenCL, serves as a drop-in replacement for OpenMP applications
- use any compiler like on the command line
  - ⇒ LLVM/JIT is not enough
  - ⇒ need specific vendor optimisations (Intel, Cray, . . .)
  - ⇒ maximum flexibility

⇒ enables compiler optimisations based on runtime-data

  - conditionals, loops, memory access, vectorisation, . . .

KART API concepts

- **program**
  - created from source code
  - can be built
  - contains kernels
- **toolset**
  - config files:

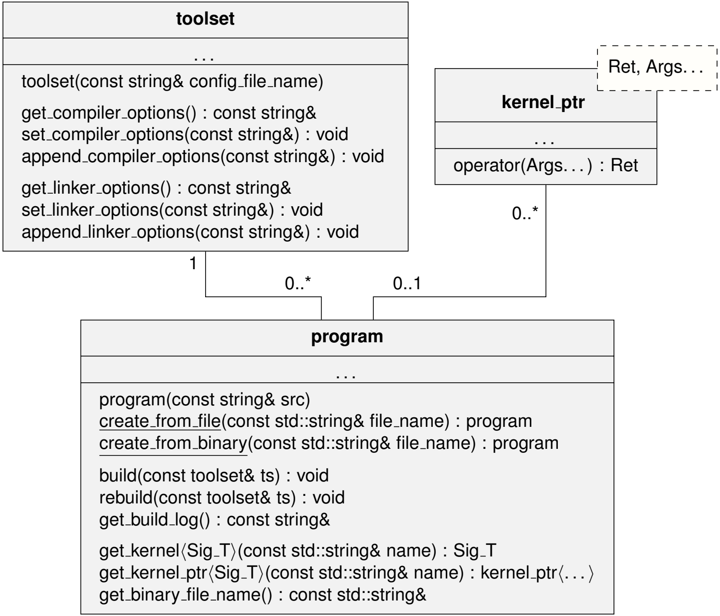
```
[compiler]
exe=/usr/bin/g++
options-always=-c -fPIC
options-default=-g -std=c++11 -Wall

[linker]
exe=/usr/bin/g++
options-always=-fPIC -shared
options-default=-g -Wall
```

  - `export KART_DEFAULT_TOOLSET=gcc.kart`

- **kernel_ptr**
  - type-safe callable template
  - can be used like any function

KART API



toolset

. . .

toolset(const string& config_file_name)

get_compiler_options() : const string&
set_compiler_options(const string&) : void
append_compiler_options(const string&) : void

get_linker_options() : const string&
set_linker_options(const string&) : void
append_linker_options(const string&) : void

Ret, Args. . .

kernel_ptr

. . .

operator(Args. . .) : Ret

program

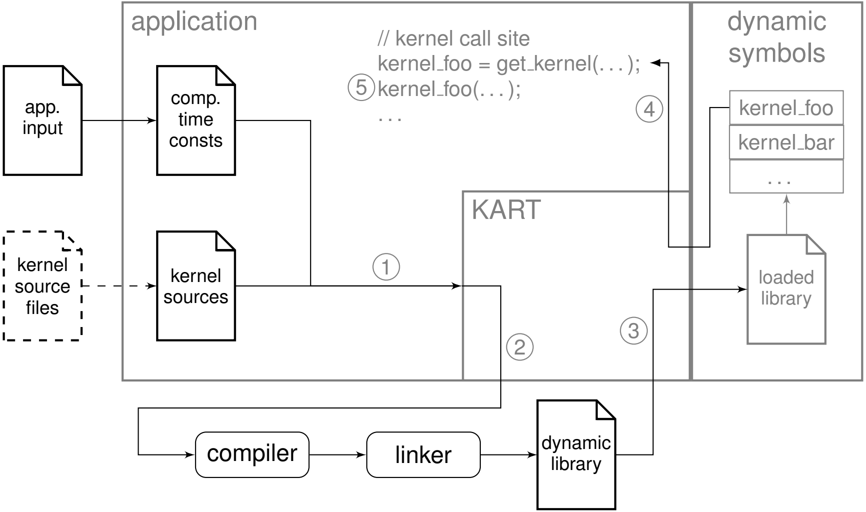
. . .

program(const string& src)
create_from_file(const std::string& file_name) : program
create_from_binary(const std::string& file_name) : program

build(const toolset& ts) : void
rebuild(const toolset& ts) : void
get_build_log() : const string&

get_kernel⟨Sig_T⟩(const std::string& name) : Sig_T
get_kernel_ptr⟨Sig_T⟩(const std::string& name) : kernel_ptr⟨. . . ⟩
get_binary_file_name() : const std::string&

KART Implementation



KART C++ example

```
// original function
double my_kernel(double a, double b)
{ return a * b * CONST; }
```

```
int main(int argc, char** argv)
{






  /* ... application code ... */

  // call the kernel as usual
  double res = my_kernel(3.0, 5.0);

  /* ... application code ...  */
}
```

KART C++ example

```
#include "kart/kart.hpp"

// signature type
using my_kernel_t = double(*)(double, double);
// raw string literal with source
const char my_kernel_src[] = R"kart_src(
extern "C" {

// original function
double my_kernel(double a, double b)
{ return a * b * CONST; }

})kart_src"; // close raw string literal
```

```
int main(int argc, char** argv)
{
  // create program
  kart::program my_prog(my_kernel_src);
  // create default toolset
  kart::toolset ts;
  // append a constant definiton (runtime value)
  ts.append_compiler_options(" —DCONST=5.0");
  // build program using toolset
  my_prog.build(ts);
  // get the kernel
  auto my_kernel =
       my_prog.get_kernel<my_kernel_t>("my_kernel");

  /* ... application code ... */

  // call the kernel as usual
  double res = my_kernel(3.0, 5.0);

  /* ... application code ...  */
}
```

WIP: selecting runtime-compiled source via annotations

```
BEGIN_KART_COMPILED_CODE(my_kernel, double(*)(double, double))
double my_kernel(double a, double b)
{
    return a * b;
}
END_KART_COMPILED_CODE()
```

Idea:

- easier adaptation of existing code
- use preprocessor to generate wrapping code around functions
- **kernel name** and **type** are specified manually

⇒ can be **enabled/disabled** globally per define

Problem:

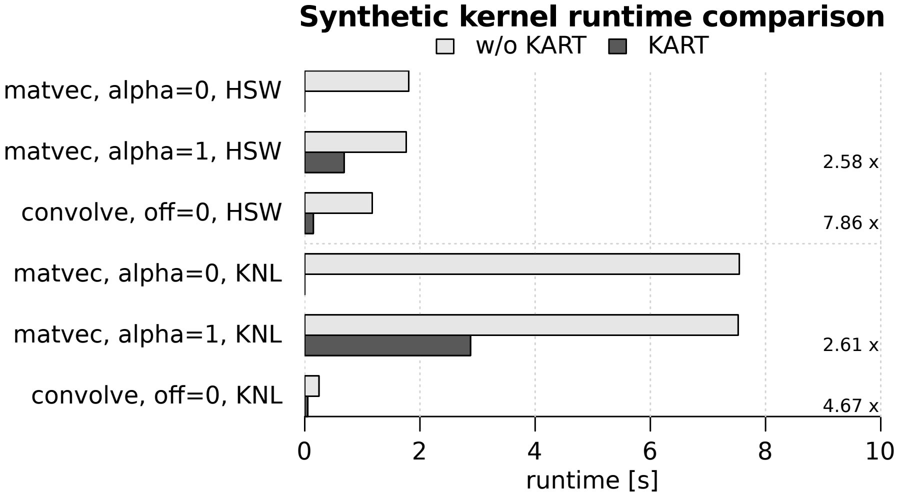
- edgy use of preprocessor
  - only works with "g++ -E", followed by compilation (not in a single command)

Benchmarks - Synthetic Kernels

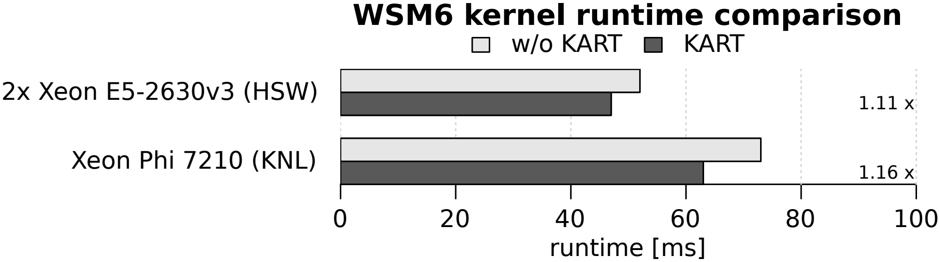
```
extern "C"
void matvec_kart(float a[][COLS],
                 float b[ROWS],
                 float x[COLS])
{
  for (int i = 0; i < ROWS; ++i)
    for (int j = 0; j < COLS; ++j)
      b[i] += a[i][j] * x[j] * ALPHA;
}
```

```
extern "C"
void convolve_kart(float* restrict input,
                   float* restrict kernel,
                   float* restrict output)
{
  #pragma omp parallel for
  for (int i = 0; i < INPUT_SIZE; ++i) {
    float sum = 0;
    for (int j = 0; j < KERNEL_SIZE; ++j)
      sum += kernel[j] * input[OFF + i + j];
    output[i] = sum;
  }
}
```

Benchmarks - Synthetic Kernels

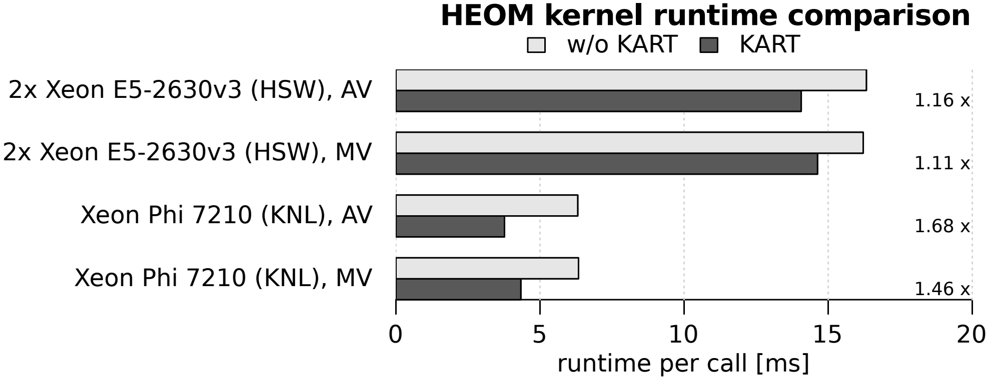


Benchmarks - WSM6 (Fortran)



WSM6 - the WRF SIngle Moment 6-class Microphysics schema - is part of the Weather Research and Forecast (WRF) model, widely used for numerical weather prediction.

Benchmarks - HEOM Hexciton Benchmark



HEOM - Hierarchical Equations of Motion - is a model for computing open quantum systems, e.g. used to simulate energy transfers in photo-active molecular complexes.

Compilation Overhead

Runtime compilation techniques pay off when the accumulated runtime savings of all kernel calls exceed the runtime compilation cost.

- speed-up of the runtime-compiled kernel over the reference kernel:

$$s_b = \frac{t_{\text{ref}}}{t_{\text{kart}}}, \quad t_{\text{ref}} > t_{\text{kart}} \;\Rightarrow\; s_b > 1$$

- s_b is an upper bound for the actual speed-up s including compilation overhead, where n is the number of kernel runs:

$$s = \frac{n \cdot t_{\text{ref}}}{n \cdot t_{\text{kart}} + t_{\text{compile}}}$$

- number of calls n_c needed to amortise t_{compile}:

$$n_c = \frac{t_{\text{compile}}}{t_{\text{ref}} - t_{\text{kart}}}$$

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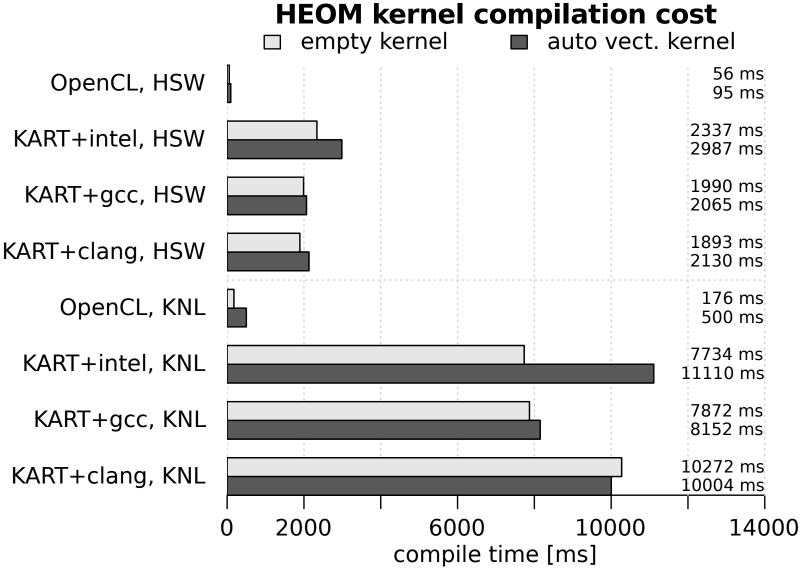
HEOM:
$n_c \approx 10^3, \; n_{90} \approx 10^4, \; n \approx 10^5$

Benchmarks - Compile Time



Goal: Reduce compile time overhead

Ideally:

- Standardised library API provided by compilers
  - ⇒ no processes
  - ⇒ no file operations
  - ⇒ no network operations (e.g. license server)
- OpenMP directives (with same compilers)

Goal: Reduce compile time overhead

Next steps:

- add **LLVM/MCJIT** as backend (approach C.) to save compile time where LLVM yields sufficient code
  - ⇒ see how much overhead remains (without process creation and file I/O)

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- implement **automatic kernel cache**
  - ⇒ cache the generated libs with checksums based on source, toolchain, and options
  - ⇒ similar to PoCL (OpenCL implementation using the LLVM toolchain like KART)

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  - ⇒ similar to PoCL (OpenCL implementation using the LLVM toolchain like KART)
- compilation **server/deamon**
  - ⇒ global kernel-cache (more re-use)
  - ⇒ compile fast on Xeon, run fast on Xeon Phi
  - ⇒ limit license use

Runtime compilation allows much more

- **benchmarking/auto-tuning** of kernels based on input data
- can be combined with source **code generation** techniques
- different variants of the same kernel
  - even from different compilers/versions
- single binary for different SIMD instruction sets (even unknown ones)
- cross language use
- . . .

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Example

- benchmark math function on HLRN-III Cray XC40 supercomputer
  1. host application compiled with Cray compiler
  2. generates benchmark kernel source from template
  3. compiles and links in code with Cray, Intel, Clang, and GCC
  4. benchmarks kernels

  ⇒ . . . and it works!

EoP - Thank you!

- The code will be available soon:
  - ⇒ `https://github.com/noma/kart`
    - ⇒ click "Watch" and wait
    - ⇒ or send me a mail
  - ⇒ Boost Software License (BSD/MIT-like)
- Questions, use cases, ideas, . . . ?
  - ⇒ contact me: noack@zib.de
- Paper:
  - ⇒ M. Noack, F. Wende, G. Zitzlsberger, M. Klemm, T. Steinke, *KART—A Runtime Compilation Library for Improving HPC Application Performance*,
    ISC'17 Workshop Proceedings