Automated OpenCL GPU kernel fusion for Stan Math

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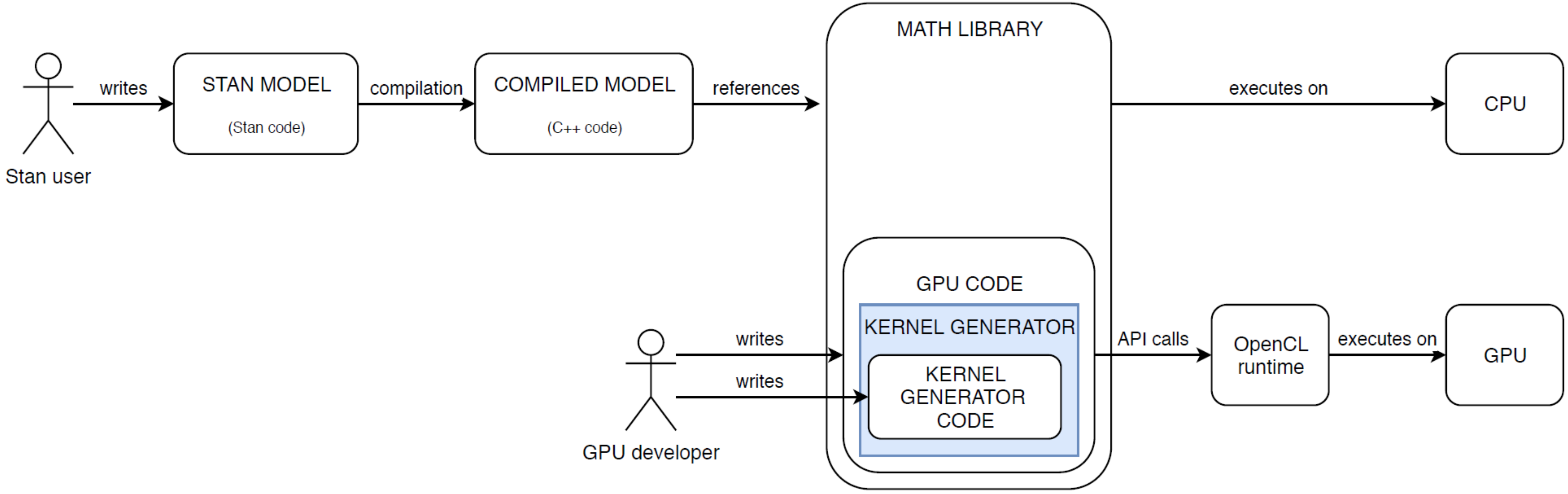
Stan

- State-of-the-art software for Bayesian statistics.
- Probabilistic programming language + Math library with auto-differentiation + Inference algorithms.
- Some operations have an OpenCL implementation.

Overview

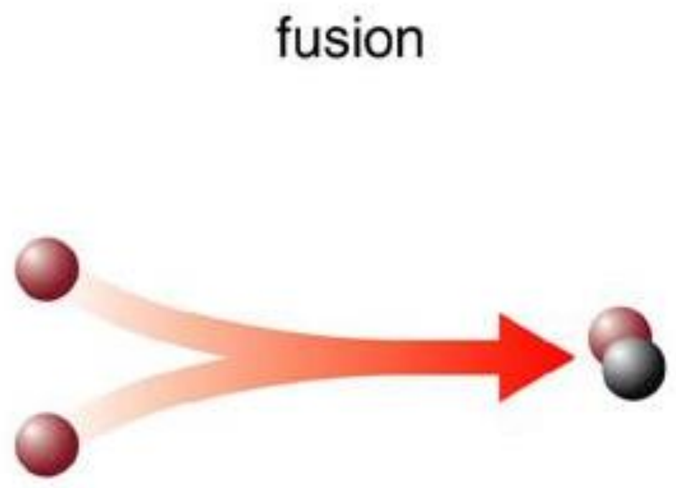

Stan user
writes
STAN MODEL
(Stan code)
compilation
COMPILED MODEL
(C++ code)
references
MATH LIBRARY
executes on
CPU
GPU CODE
KERNEL GENERATOR
KERNEL GENERATOR CODE
GPU developer
writes
writes
API calls
OpenCL runtime
executes on
GPU

GPU development in the Stan Math library

- Hundreds of possible operations and distributions to implement for GPUs.
- Sequence of basic kernels: simple to develop, poor performance.
- Specialized kernels: good performance, slow development.

Kernel fusion

- Execution of multiple operations in a single kernel.
- Speedup: kernel launch overhead, memory transfers between registers and global memory.
- Can be automated.
- Data fusion.
- Parallel fusion.



Implementation: interface

Lazy evaluation:

- Operations are C++ objects,
- expression is evaluated when assigned to result matrix.

Curiously Recurring Template Pattern:

```
template <typename T_a, typename T_b>
class addition_ : public binary_operation<addition_<T_a, T_b>, T_a, T_b> {
 public:
  addition_(T_a&& a, T_b&& b)
      : binary_operation<addition_<T_a, T_b>, T_a, T_b>(
            std::forward<T_a>(a), std::forward<T_b>(b), "+") {}
};

template <typename T_a, typename T_b,
          typename = require_all_valid_expressions_t<T_a, T_b>>
inline addition_<as_operation_cl_t<T_a>, as_operation_cl_t<T_b>> operator+(T_a&&
a, T_b&& b) {
  return {as_operation_cl(std::forward<T_a>(a)),
          as_operation_cl(std::forward<T_b>(b))};
}
```

Implementation: operation types

Example:

```
matrix_cl<double> a, b;
double c;
matrix_cl<double> d = c * (a + b);
```

`a + b`

```
addition_<load_<matrix_cl<double>&>, load_<matrix_cl<double>&>>
```

`c * (a + b)`

```
elewise_multiplication_<scalar_<double>, addition_<load_<matrix_cl<double>&>, load_<matrix_cl<double>&>>>
```

Assignment of an expression to a matrix generates, compiles and executes a kernel.

Implementation: generating kernel code

Operation objects generate code for their operation:

_load:

```
double [NAME] = 0;
if (!((!contains_nonzero([NAME]_view, LOWER) && j < i) ||
     (!contains_nonzero([NAME]_view, UPPER) && j > i))) {
  [NAME] = [NAME]_global[i + [NAME]_rows * j];
}
```

_addition:

```
double var4 = var2 + var3;
```

_load:

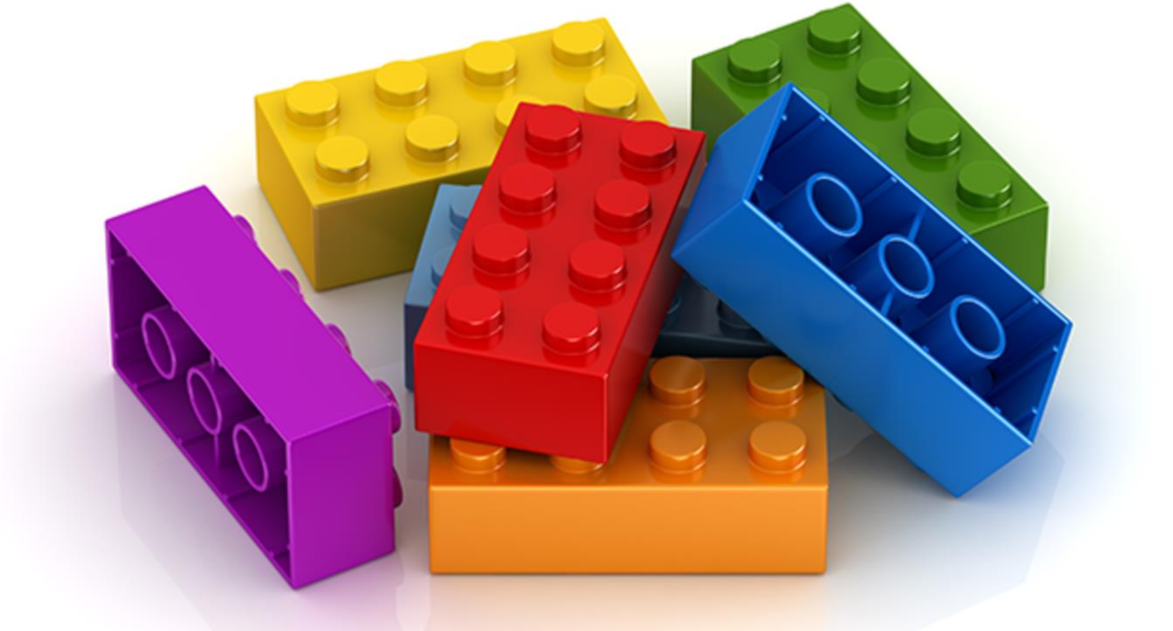
```
var5_global[i + var5_rows * j] = var4;
```

Complete kernel

```
kernel void calculate(__global double var1,
   __global double* var2_global, int var2_rows, int var2_view,
   __global double* var3_global, int var3_rows, int var3_view
   __global double* var6_global, int var6_rows, int var6_view){
  int i = get_global_id(0);
  int j = get_global_id(1);
  double var2 = 0;
  if (!((!contains_nonzero(var2_view, LOWER) && j < i) ||
   (!contains_nonzero(var2_view, UPPER) && j > i))) {
     var2 = var2_global[i + var2_rows * j];
  }
  double var3 = 0;
  if (!((!contains_nonzero(var3_view, LOWER) && j < i) ||
    (!contains_nonzero(var3_view, UPPER) && j > i))) {
    var3 = var3_global[i + var1_rows * j];
  }
  double var4 = var2 + var3;
  double var5 = var1 * var4;
  var6_global[i + var6_rows * j] = var5;
}
```

Adding a new operation

- New class for the operation (derived from **operation_cl** or **operation_cl_lhs**).
- Must define:
  - `Scalar`,
  - `generate`,
  - `view`.
- Optional: `generate_lhs`, `rows`, `cols`.
- A function that constructs the object.

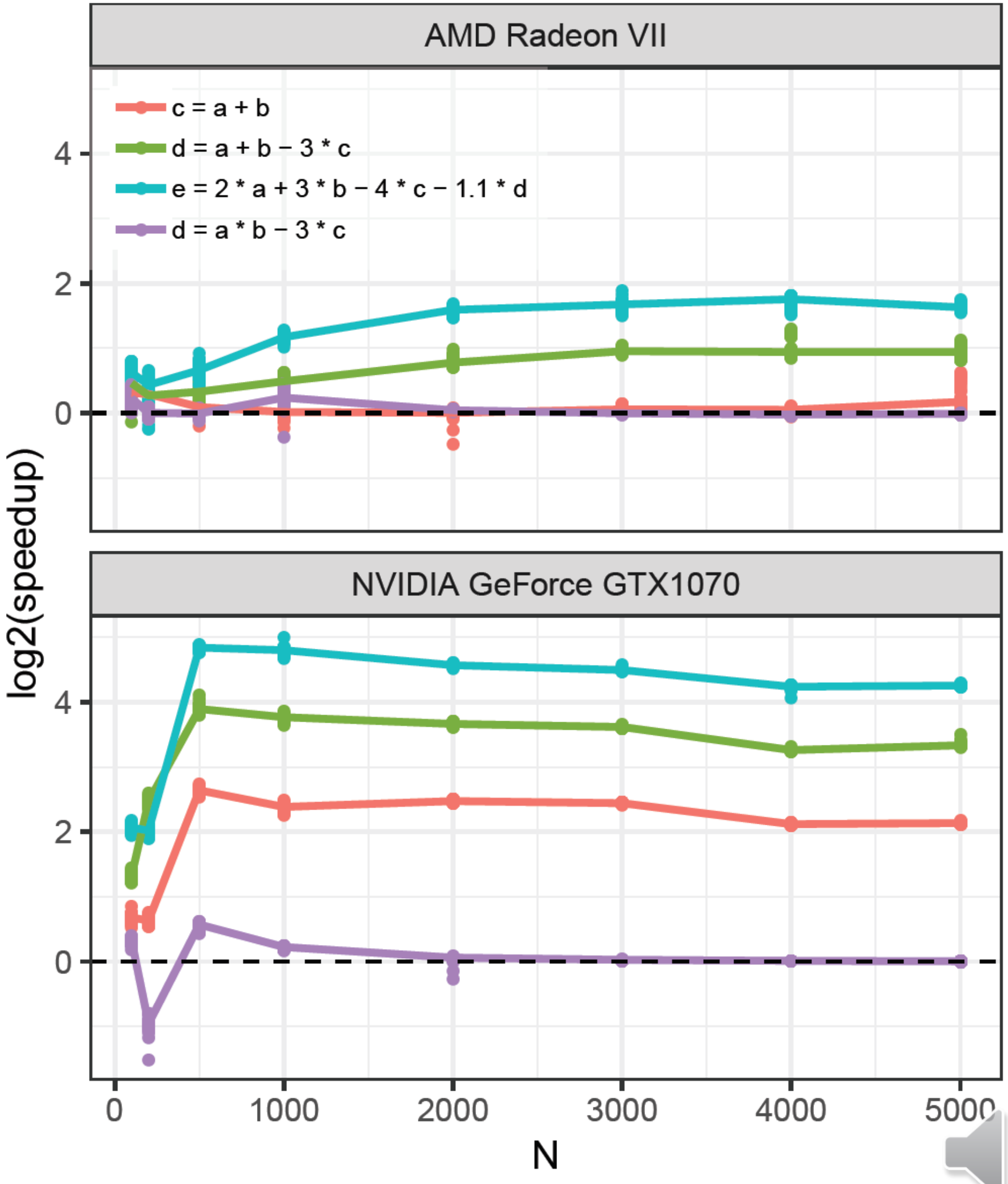


Empirical validation

- Comparison with a sequence of basic kernels.
- Comparison with a hand crafted kernel.
- Comparison with VexCL, a similar library.
- On NVIDIA GeForce GTX 1070 and AMD Radeon VII.

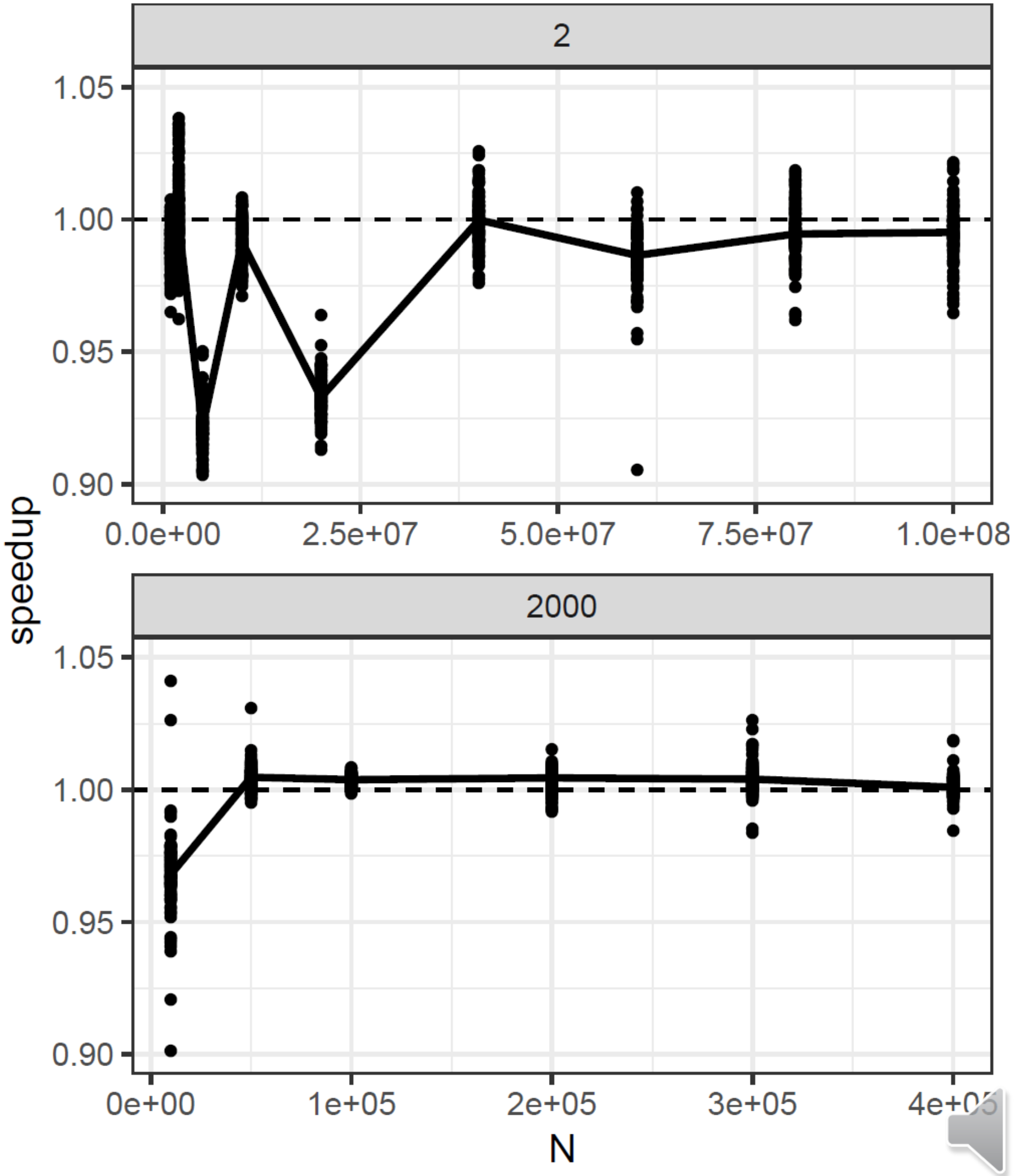
Comparison with a sequence of basic kernels

- Single operation kernel is comparable.
- Sequence is much faster.
- Matrix multiplication is slow, so speedups are negligible.
- We also avoid memory reallocations, which are slow on NVIDIA GPU.



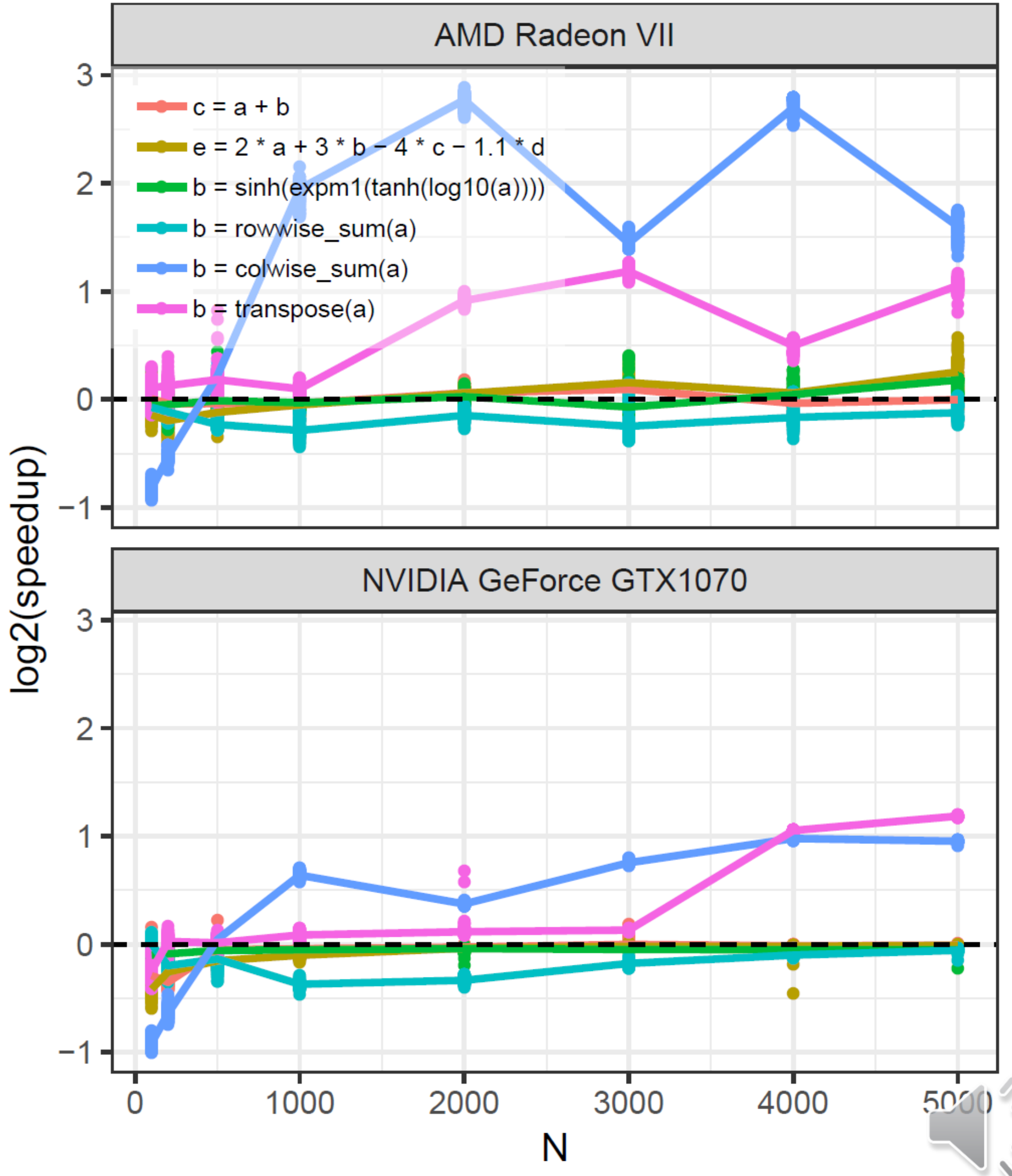
Comparison with a hand crafted kernel

- On Bayesian linear regression.
- Comparable performance.
- Much simpler to use.



Comparison with VexCL

- Transposition and colwise sum are much faster.
- Rowwise sum is slightly slower.
- Other operations and multi-operation kernels are comparable.
- Also supports general tensors and multiple OpenCL devices.



Conclusion

- Performance is comparable to hand crafted kernels.
- As simple to use as calling premade kernels.
- Our work is similar to VexCL and Tensorflow XLA.