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WebCL Validator and Memory Protection

Mikael Lepistö, Vincit Ltd
2014-01-29

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Professionals for embedded systems, linux drivers, compiler development, mobile development, web services and more.

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Mikael Lepistö

Passionate Software Engineer @Vincit
mikael.lepisto@vincit.fi

Lead developer of WebCL C memory protection

Around 10 years experience on
compilers and custom processor design toolset
(@Tampere University of Technology)

Contributer in:
LLVM/Clang
Portable OpenCL Driver

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Today

Features

Implementation

Usage

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What was committed to deliver

Phase 1 (response to the RFQ Khronos sent):

✓ Local and private memory initialisations
✓ Verify restrictions from WebCL draft
✓ Unit test cases for every feature
✓ Command line client to do instrumentation
✓ Support for safe builtin function like get_global_id()

Phase 2a (there were some budget left from phase 1):

✓ Builtin support for image builtins and vstore/vload
✓ Expose kernel arguments as JSON is start comment of instrumented code

Phase 2b (continuation project) – Critical Features by end of January 2014:

✓ Complete builtin support
✓ Library API for integrating validator
✓ Update original LLVM/Clang 3.2 to 3.4

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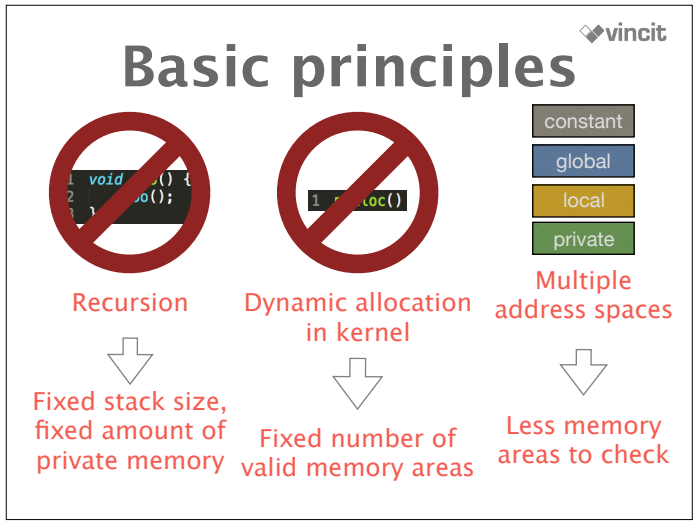
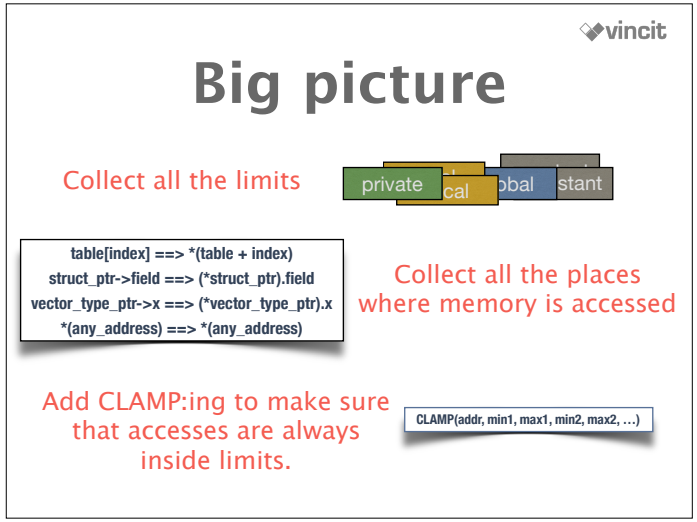
Some Features

- Parse and validate WebCL C against spec
- Extensive error messages
- LLVM/Clang 3.4 source to source transformation
- C API + static library
- Optimised validation time performance
- Extensive test bench
- Adds size arguments for buffers passed to kernel
- Collect and exposes information about kernel argument types
- Forces private and local memory initialisation
- Run time checks to make all memory accesses safe
- Automatic generation for safe builtins, to protect from potentially dangerous builtin invokes
- Check sampler_t usage to be correct at instrumentation time
- Complete suport for WebCL builtins
- Collection of statically allocated variables of address spaces to reduce number of valid memory areas
- Reorganisation of type declarations to make them available for address space structures
- Renaming of moved variables to prevent collision of variables of different scopes by the same name
- Find biggest memory access and memory alignment requirements for each address space
- Finds and adds code to select valid area for each address space null pointer
- Adds arguments to all helper functions to be able to pass memory limit structure to be available in helper functions
- Restricted goto statement
- Instrumentation time generation for program specific memory clamping macro
- Restricted image support only for image2d_t
- Restricted identifier names to 256 characters



- If malloc/free are supported as pool allocation, it won't affect to method.
- If there is real dynamic allocation support, also that part of bookkeeping of memory areas must be implemented dynamically.



- When program enters the kernel, all valid memory areas are stored to bookkeeping structure.
- All the memory accesses are normalised to *(address) form, to make same type of clamping to work for everything.
- Protected memory access would look like *(CLAMP(address, valid_range_min, valid_range_max)).
- CLAMP(address, valid_range_min, valid_range_max) returns given address if in range or address to address space specific NULL which has valid alignment and size to fulfil safely any of the programs memory accesses.

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How memory is allocated for different address spaces

```
constant int magic = 10;

kernel void example_kernel(
  global float* out,
  constan float* factors,
  local float* scratch) {

  local float static_local_memory[10];
  int index = get_global_id(0);
  // TODO: do something useful here ..
}
```

private

local

global

constant

- Global memory: Can be only passed in kernel arguments.
- Constant memory: Can be passed in arguments or allocated statically.
- Private memory: Only static allocation possible.
- Local memory: Static allocation and may be passed to kernel.
- These are ALL of the valid memory areas, where program should access.

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Add bookkeeping to kernel start

```
constant int magic = 10;

kernel void example_kernel(
   global float* out,
   constan float* factors,
   local float* scratch) {

   local float static_local_memory[10];
   int index = get_global_id(0);
   // TODO: do something useful here ..
}
```

Add arg sizes

```
constant int magic = 10;

kernel void example_kernel(
   global float* out, ulong out_size,
   constan float* factors, ulong factors_size,
   local float* scratch, ulong scratch_size) {

   local float static_local_memory[10];
   int index = get_global_id(0);
   // TODO: do something useful here ..
}
```

Memory area bookkeeping

AS	start	end
constant	&magic	&magic + 1
constant	&factors[0]	&factors[size]
global	&out[0]	&out[size]
local	&scratch[0]	&scratch[size]
local	&sec…ratch[0]	&sec…ratch[size]
private	&index	&index + 1

- Now when we enter to kernel we know ALL the memory areas that program should be allowed to access.
- When kernel is started, instrumentation collects all the limits of separate memory areas to bookkeeping structure.
- To be able to know end of memory areas passed in kernel arguments, also size arguments must exist for buffers.
- We add second argument for each memory buffer that is passed, which tells element count.
- Size arguments cannot be given by end user, but WebCL host API implementation must set value correctly.

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Memory accesses

table[index] ==> *(table + index)
struct_ptr->field ==> (*struct_ptr).field
vector_type_ptr->x ==> (*vector_type_ptr).x
*(any_address) ==> *(any_address)

*(address) ==> *(CLAMP(addr, min1, max1, min2, max2, ...))

Instrumentation does not cause any restrictions to pointer arithmetics, casting etc.

- There might be need to do multiple memory limit checks if there are many limits in bookkeeping for the same address space.
- To reduce number of memory areas, we collect all the static allocations to structs, one per address space to minimise number of limit checks.
- Functionality of builtins is well defined, so if they are potentially dangerous, they are wrapped to safe versions, which first checks if call is safe before executing actual builtin.

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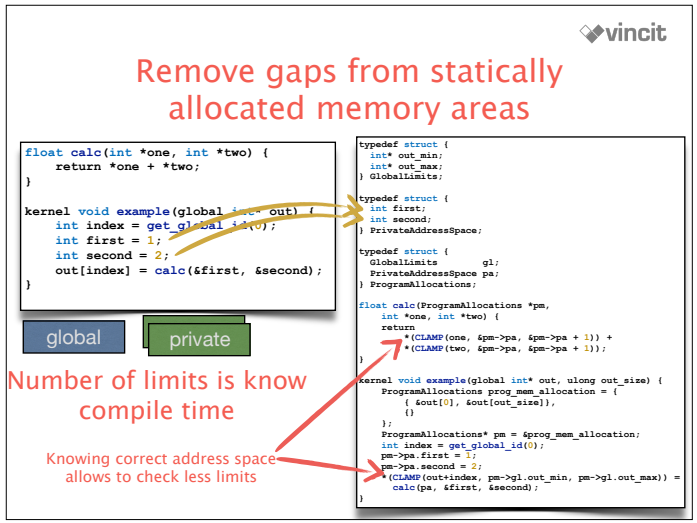
Builtins

```
vload2(offset, f);
```

```
float2 _wcl_vload2_0(
_WclProgramAllocations* _wcl_allocs, size_t arg0, const __global float * arg1)
{
    const __global float * ptr = arg1 + 2 * (size_t) arg0;
    if (_wcl_addr_check_global_2_const___u_uglobal__float__Ptr(ptr, 2,
(const __global float *)_wcl_allocs->gl.builtin_wrappers__output_min,
(const __global float *)_wcl_allocs->gl.builtin_wrappers__output_max,
(const __global float *)_wcl_allocs->gl.builtin_wrappers__f_min, (const __global float
*)_wcl_allocs->gl.builtin_wrappers__f_max))
        return vload2(0, ptr);
    else
        return (float) 0;
}
```

```
_wcl_vload2_0(_wcl_allocs, _wcl_locals._wcl_offset, f);
```

- For builtin calls safe builtin implementations are generated
- Safe builtin version makes sure that no invalid memory will be accessed before calling the real builtin.



- Compiler collects all the memory accesses and makes them to continuous area.
- Bookkeeping structure is initialised in the start of kernel (prog_mem_allocation variable).
- Bookkeeping structure is passed to helpers (ProgramAllocations *pm).
- Global memory access is normalised to *() format before clamping (was out[index]).
- Index variable is not collected to private address space, because there is no address reference to it.

- The same code instrumented by WebCL memory protector.
- 50-100 lines of macro declarations and comments were stripped from output.
- More information of real instrumentation phases will follows in next section.

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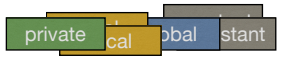
Recap

Collect all the limits




```
table[index] ==> *(table + index)
struct_ptr->field ==> (*struct_ptr).field
vector_type_ptr->x ==> (*vector_type_ptr).x
*(any_address) ==> *(any_address)
```

Collect all the places where memory is accessed

Add CLAMP:ing to make sure that accesses are always inside limits.

```
CLAMP(addr, min1, max1, min2, max2, ...)
```

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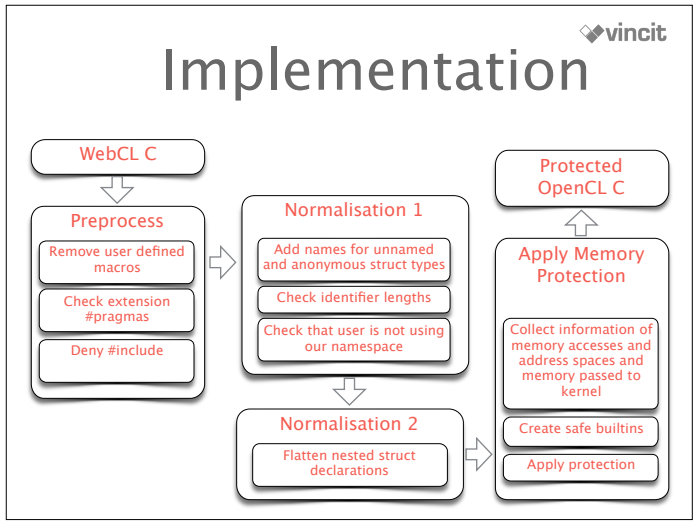
Stack smashing

- All memory writes, also those which are done by builtins are protected.
- Cannot write to area that is outside of min,max limits of address space.
- E.g. return address is stored outside of that area.

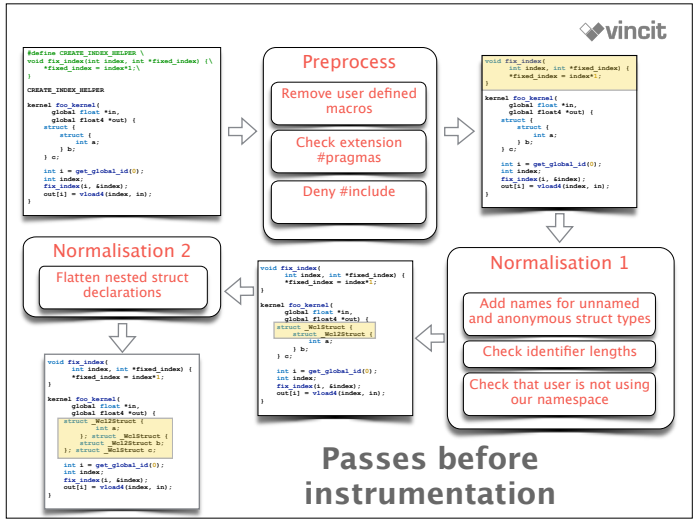
Stack starting from kernel exec

global min addr	Accessed only by instrumeted code (_WclProgramAllocations)
global max addr	
…	
global null pointer	
local min addr	
local max addr	
…	
local null pointer	
private as var 1	Stack variables that can be accessed through address ref.
private as var 2	
private as var 3	
…	
other private var 1	Can be accessed only as values there is never address reference to these.
other private var 2	
…	
return ptr	
…	

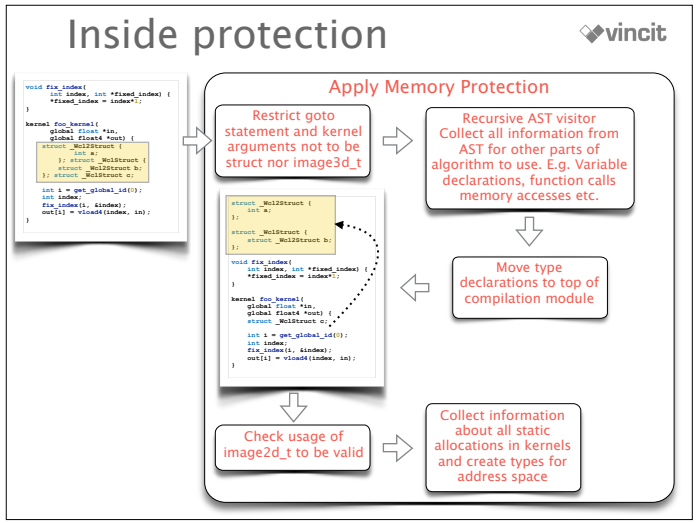
- Green area is where the variables are places, which has potentially access through pointer. This can be written and read by user code.
- Rest cannot be written / read by user code (all accesses of private address space are clamped to green area)
- All builtins are protected so e.g. if we would have classic buffer overflow by strcpy, our safe implementation would prevent it from writing over address space limits.
- Because only green area can be accessed by user code or builtins, return address cannot be overridden.



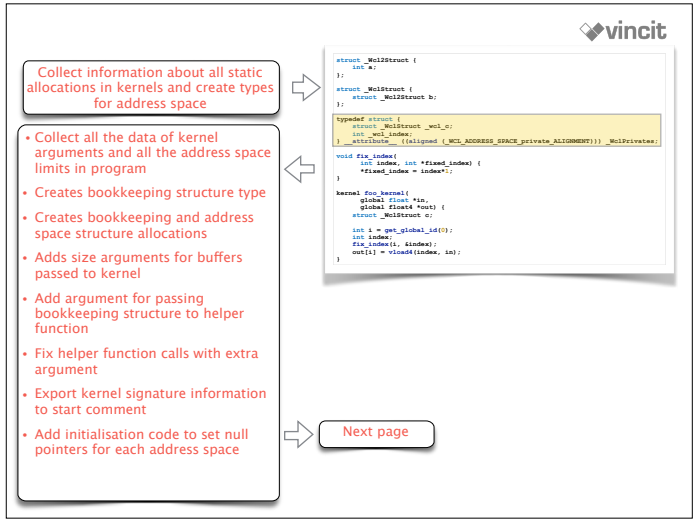
- In high level validation and protection is implemented in 4 passes.
- Preprocessor, Normalisation 1, Normalisation 2, Protector.
- Source is re-written and parsed again between each pass.



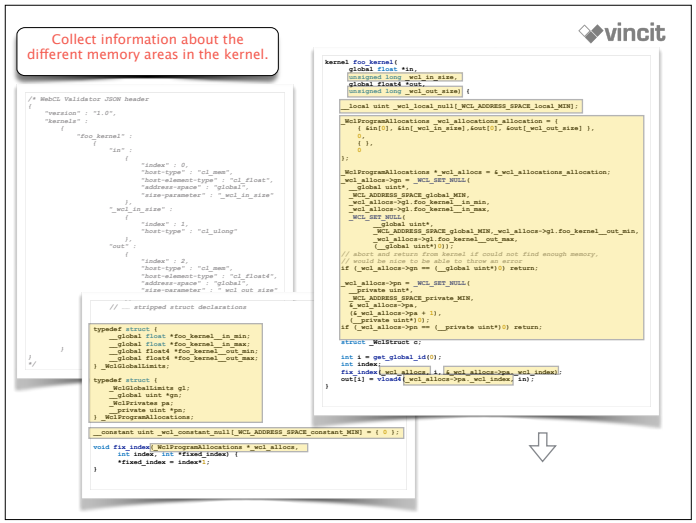
- Yellow parts are the changes done in code.
- Normalisation passes are important to make final protection pass more simple.



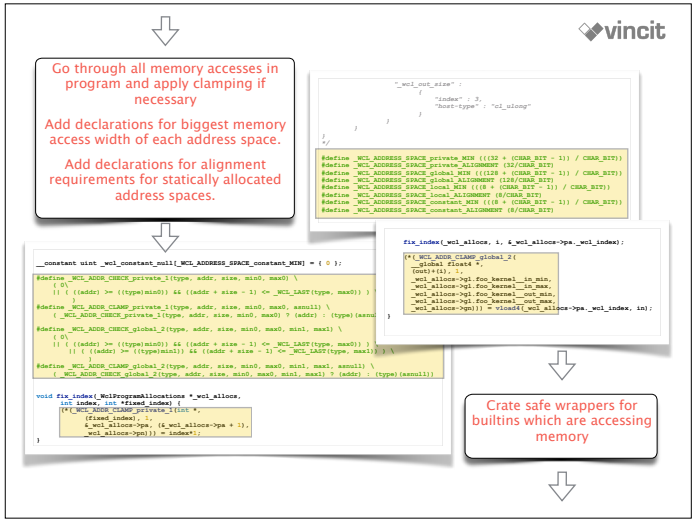
- Inside memory protector pass source code is not re-written / re-parsed.
- Declarations must be in early in compilation module to be able to use all the types in address space structures.



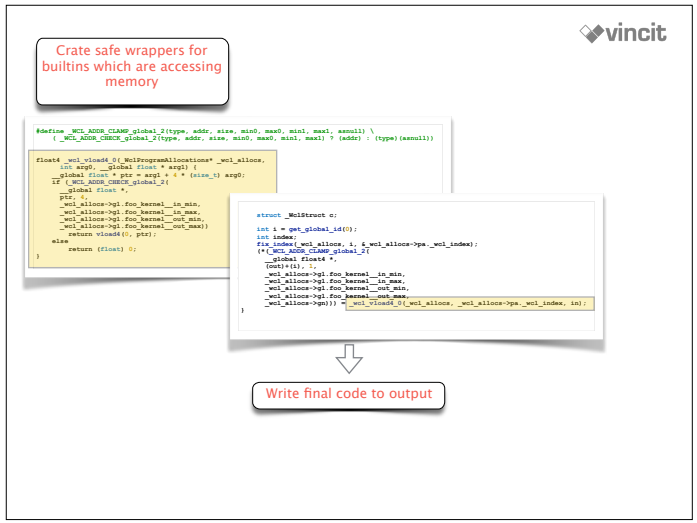
- Information about address spaces is collected.
- Type declarations for address spaces are created.



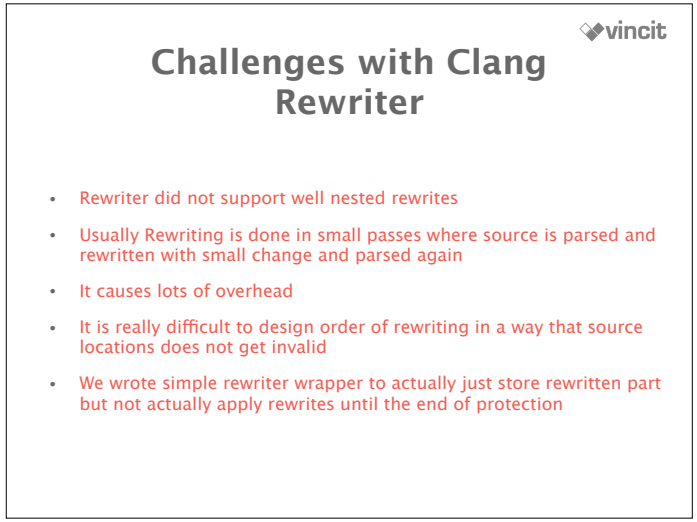
- Data about kernel arguments is collected.
- Limit bookkeeping structure type declarations are created.
- Constant address space is allocated.
- Bookkeeping struct argument is added to helper functions.
- Size arguments are added to kernel argument list.
- Bookkeeping structure is allocated and initialised with memory limits.
- Code to find big enough memory areas to set null pointers for every address space is added to kernel initialisation.
- References to variables that are relocated to address space structure are fixed to refer address space struct fields (i.e. _wcl_alloca->pa._wcl_index).



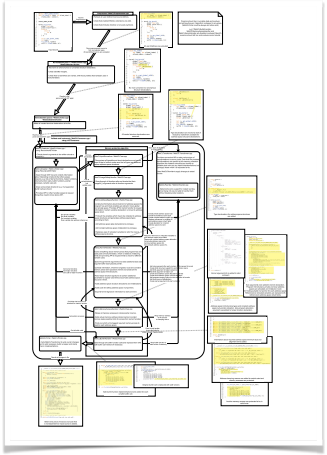
- Clamping macros are created.
- Memory protection calls is added to every memory access.
- Biggest memory access size of every address space is resolved.
- Alignment requirements for address space allocations are resolved.



- Find all builtin calls and create safe versions of them if necessary.
- Fix calls to builtins to use safe versions.
- Write the final code to file / string.



- With clang-3.2 rewriter didn't support complex rewriting.
- We added own wrapper for clang rewriter to allow some nested rewrites.
- When our rewriter applies changes it first internally flattens nested rewrites, so that we don't have to do any overlapping rewrites with clang.



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Detailed flow chart is in github doc folder:

- different program modules
- Usage of Clang classes
- responsibilities of different passes
- communication between modules

https://github.com/KhronosGroup/webcl-validator/blob/master/doc/InstrumentationFlowChart.pdf

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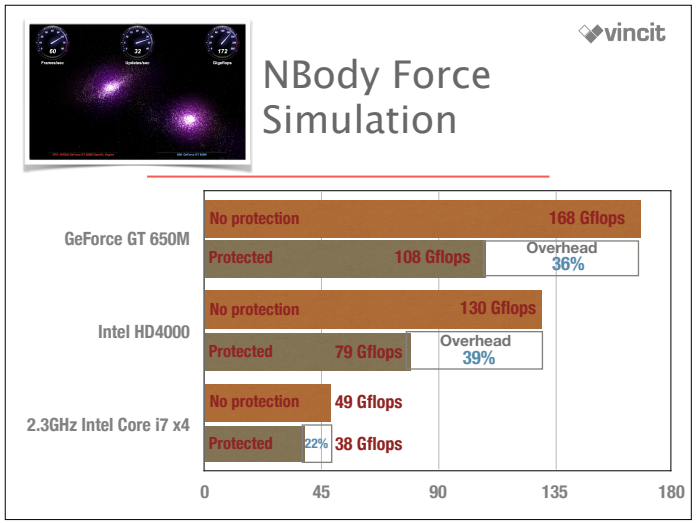
Demo 1

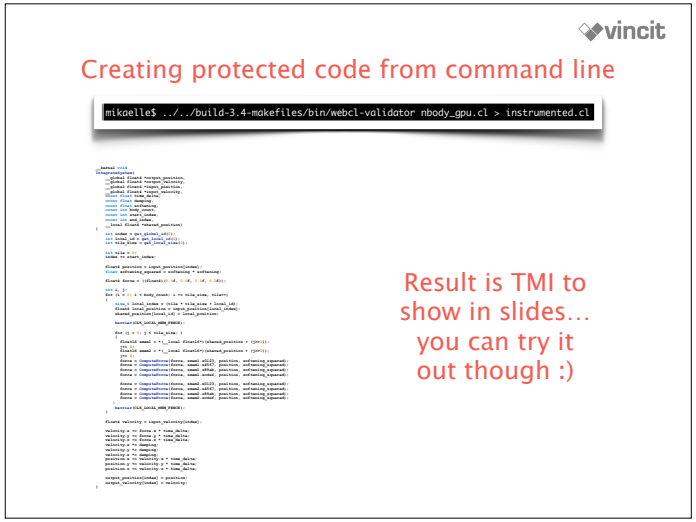
```
barrier(CLK_LOCAL_MEM_FENCE);
for (j = 0; j < tile_size; )
{
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);

    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
}
barrier(CLK_LOCAL_MEM_FENCE);
```

- 8 time unrolled loop that has one float4 load on every call to helper function.



- Typical case of overhead caused by instrumentation.
- Basic implementation of the protection method.
- No special optimisations implemented.
- Not even the most simple static analysis is done to eliminate unnecessary checks / nor ordering of checks so that most probably area would be checked first.



- WebCL validator can be executed from command line
- We offer also library API, which command line client is also using internally.

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How the overhead could be reduced?

- Less than 50% overhead is already really good starting point
- What coder can do to make it faster?

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Coding conventions

Always read big block from memory

Don't use arrays in private address space

Constant length of loops and as simple indexing operations as possible

- Most importantly access memory in as big blocks as possible -> Less run time checks.
- These same guidelines should help you out with any OpenCL code.
- Constant length loops with simple indexing can make it possible to move checks from inside of loop to before loop (currently there is no this kind of optimisations).

Demo 1 Optimised

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```
barrier(CLK_LOCAL_MEM_FENCE);
for (j = 0; j < tile_size; )
{
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);

    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
    force = ComputeForce(force, shared_position[j++], position, softening_squared);
```

float4 access x8

```
barrier(CLK_LOCAL_MEM_FENCE);
for (j = 0; j < tile_size; )
{
    float16 smem1 = *(__local float16*)(shared_position + (j>>2));
    j+= 4;
    float16 smem2 = *(__local float16*)(shared_position + (j>>2));
    j+= 4;

    force = ComputeForce(force, smem1.s0123, position, softening_squared);
    force = ComputeForce(force, smem1.s4567, position, softening_squared);
    force = ComputeForce(force, smem1.s89ab, position, softening_squared);
    force = ComputeForce(force, smem1.scdef, position, softening_squared);

    force = ComputeForce(force, smem2.s0123, position, softening_squared);
    force = ComputeForce(force, smem2.s4567, position, softening_squared);
    force = ComputeForce(force, smem2.s89ab, position, softening_squared);
    force = ComputeForce(force, smem2.scdef, position, softening_squared);
}
barrier(CLK_LOCAL_MEM_FENCE);
```

float16 access x2

- Changed core loop of kernel
- Before: 8 times reading float4 from local memory
- After: 2 times read float16 form local memory
- The same amount of memory accessed, but in bigger blocks.

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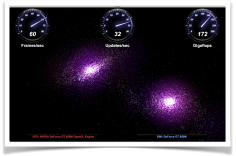
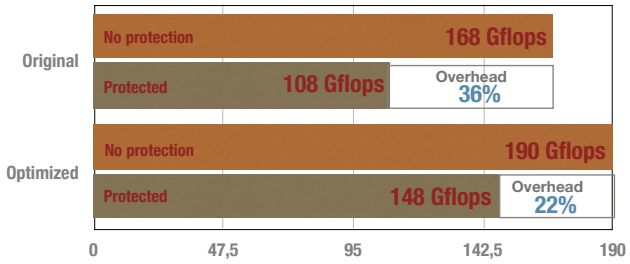
Overhead reduced by 39%



Optimized Number of Memory Accesses



- Few lines in kernel core loop was changed.
- Original code runs 12% faster.
- Overhead was reduced by 39% (from 36% -> 22%).
- In the end overhead caused by protection was 22%

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Demo 2

```
__kernel void
QJuliaKernel(
    __global uchar4 *result,
    const float4 mu,
    const float4 diffuse,
    const float epsilon)
{
    int tx = get_global_id(0);
    int ty = get_global_id(1);
    int index = ty * WIDTH + tx;
    float4 coord = (float4)((float)tx, (float)ty, 0.0f, 0.0f);
    float4 color = QJulia(coord, mu, diffuse, epsilon, ITERATIONS, SHADOWS, WIDTH, HEIGHT);
    uchar4 output = convert_uchar4_sat_rte(color * 255.0f);
    result[index] = output;
}
```

- Apple's QJulia example

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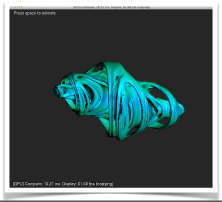
QJulia

	Original	Protected	Overhead
Intel HD4000	61 fps	61 fps	0%



- Virtually no overhead.
- Most of the initialisation code is optimised away by vendor driver.
- Just one global memory write was instrumented by protection.
- With coding conventions and better static analysis also more complicated cases would be possible to validate instrumentation time. We could e.g. resolve buffer size requirements as a function of local and global size and check those before enqueuing kernel.

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What was committed to deliver

Phase 1:
✓ Local and private memory initialisations
✓ Verify restrictions from WebCL draft
✓ Unit test cases for every feature
✓ Command line client to do instrumentation
✓ Support for safe builtin function like get_global_id()

Phase 2a:
✓ Builtin support for image builtins and vstore/vload
✓ Expose kernel arguments as JSON is start comment of instrumented code

Phase 2b – Critical Features by end of January 2014:
✓ Complete builtin support
✓ Library API for integrating validator
✓ Update original LLVM/Clang 3.2 to 3.4

Phase 2b – Rest of the budged
✘ Re-evalueate the best use for the remaining budget (was earlier allocated for some optimisations)

- Rest of the budged was decided to be used to find reduced test cases that causes our current test bench to fail with some vendor drivers.
- Also some additional checks to allowed extensions still need to be done. E.g. disable double type, if fp64 extension is not enabled.

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How can I try it out?

https://github.com/KhronosGroup/webcl-validator

- Open source
- Progress has been and is all the time visible
- Sources, issues, instructions all in https://github.com/KhronosGroup/webcl-validator

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Code from Khronos github

https://github.com/KhronosGroup/webcl-validator

C API + static library.

Command line client

- Code in Khronos Github.
- C API + static library, extensive error reporting APIs.
- Command line client. Good for trying out how instrumented code looks like.
- Some tools for testing kernels that are used by test bench (kernel-runner is used to run kernels without need to write separate host code, opencl-validator compiles kernel code with all available drivers).

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Supported platforms

Microsoft® Visual Studio®

- Build system is CMake based part of llvm/clang building.
- Testbench uses llvm's test framework that is python + shell script based.
- Currently we test this on Visual Studio, Mac and Linux.
- Build instructions are in github repository main page (README.md).
- Best test results are got with Intel CPU driver or Portable OpenCL driver (pocl).
- With other drivers usually some tests will fail e.g. due to not supported work group size etc.

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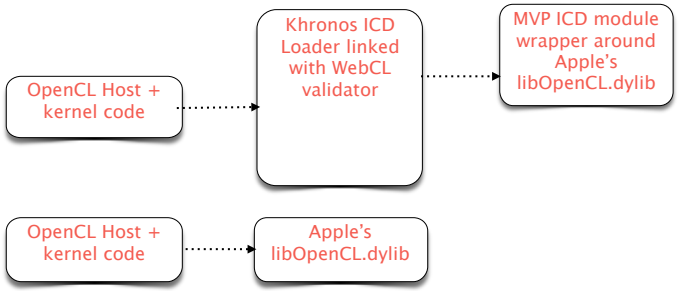
Demo: Automatic instrumentation and fixing kernel arguments



- For integrating validator one could put validation calls for example to ICD Loader, which can afterwards call vendor driver.
- In next example the same test code (OpenCL Host and Kernel code) was first linked with vendor driver.
- Then the same case was linked with ICD loader, which automatically added protection.
- Demo showed that when code was linked with protection, program was not allowed to access invalid memory anymore.
- Protection applied automatically by modified ICD Loader. No changes in OpenCL host nor kernel code.

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#include "clv/clv.h"

Link with:

liblibclv.a
libLLVMNVPTXCodeGen.a
libLLVMNVPTXDesc.a
libLLVMMCParser.a
libLLVMNVPTXInfo.a
libLLVMObjCARCOpts.a
libLLVMInstCombine.a
libLLVMipa.a
libLLVMTarget.a
libLLVMMC.a
libLLVMSupport.a
libclangASTMatchers.a
libclangFrontend.a
libLLVMOption.a
libLLVMBitReader.a
libclangParse.a
libLLVMObjCARCOpts.a
libLLVMInstCombine.a
libLLVMipa.a
libLLVMTarget.a
libLLVMAsmParser.a
libclangAnalysis.a
libclangLex.a
libLLVMMC.a
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libLLVMAsmPrinter.a
libLLVMSelectionDAG.a
libLLVMNVPTXAsmPrinter.a
libLLVMCodeGen.a
libLLVMScalarOpts.a
libLLVMTransformUtils.a
libLLVMAnalysis.a
libLLVMCore.a
libLLVMObject.a
libclangTooling.a
libclangRewriteFrontend.a
libclangDriver.a
libclangSerialization.a
libclangRewriteCore.a
libclangSema.a
libLLVMScalarOpts.a
libLLVMTransformUtils.a
libLLVMAnalysis.a
libclangEdit.a
libLLVMCore.a
libclangAST.a
libclangBasic.a
libLLVMObject.a
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- Currently only static linking is supported.
- One needs to link validator library and all the llvm libraries to which it depends.

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Thank you

Mikael Lepistö
mikael.lepisto@vincit.fi
Vincit Ltd

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