FORMALIZING ADDRESS SPACES WITH APPLICATION TO CUDA, OPENCL, AND BEYOND

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DATA LOCALITY

Data-locality plays an important role in an applications performance, e.g.:

- NUMA
- Caches (temporal and spatial)
- Address Spaces ← the subject of this talk

ADDRESS SPACES

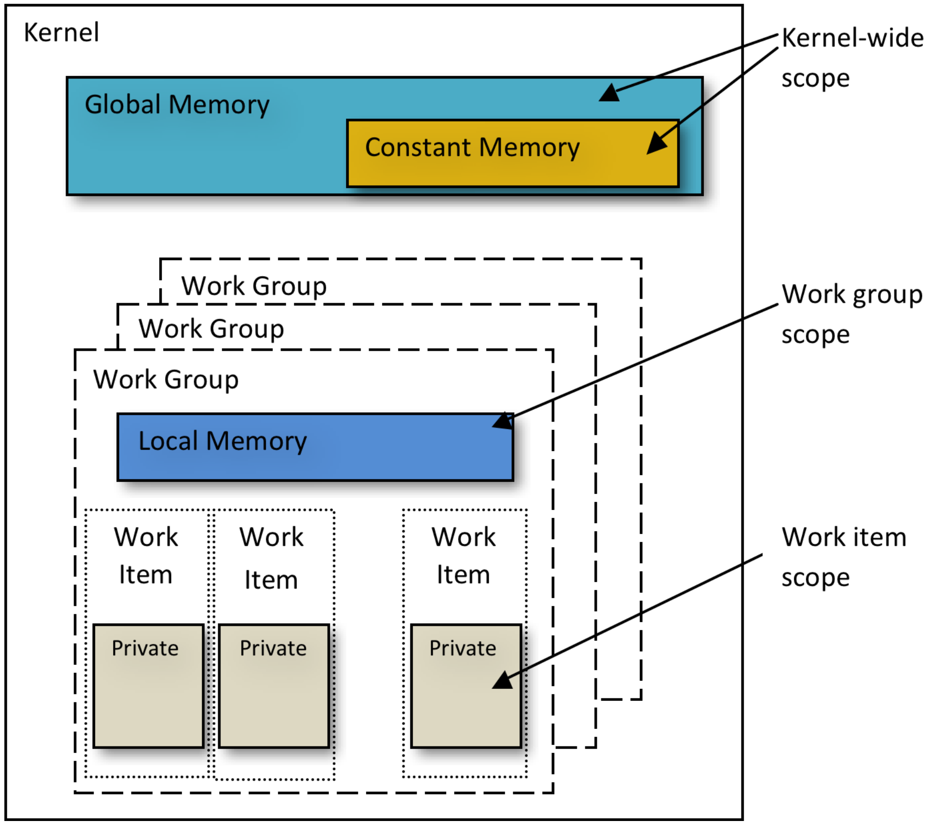
Address spaces explicitly manage where data lives during execution

Originally standardized in Embedded C

Popularized in modern GPGPU languages:

- CUDA (not formalized as part of the type system)
- OpenCL (formalized as part of the type system)

OPENCL 1.X MEMORY HIERARCHY



OPENCL - SCALE VECTOR

```
kernel void vscale(
        global int * C,
        global int * A,
        const global int * S)
{
        C[get_global_id(0)] = A[get_global_id(0)] * S[get_group_id(0)];
}
```

OPENCL ADDRESS SPACES

All pointers in an OpenCL program must be assigned an address space

OPENCL ADDRESS SPACES

Lacks the ability to parameterize over address spaces

ABSTRACT OUT SCALING TO A HELPER FUNCTION

```
int scale(global int * A, global int * S);
```

SCALE VECTOR USING ABSTRACTION

```
kernel void vscale(
            global int * C,
            global int * A,
            const global int * S)
{
  C[get_global_id(0)] = scale(&A[get_global_id(0)],  &S[get_group_id(0)]);
}
```

OPTIMIZE SCALING CONSTANTS TO ON-CHIP MEMORY

```
kernel void vscale(
            global int * C,
            global int * A,
            constant int * S)
{
  C[get_global_id(0)] = scale(&A[get_global_id(0)],  &S[get_group_id(0)]);
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OPTIMIZE SCALING CONSTANTS TO ON-CHIP MEMORY

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kernel void vscale(
            global int * C,
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  C[get_global_id(0)] = scale(&A[get_global_id(0)],  &S[get_group_id(0)]);
}
```

No longer type checks, i.e.

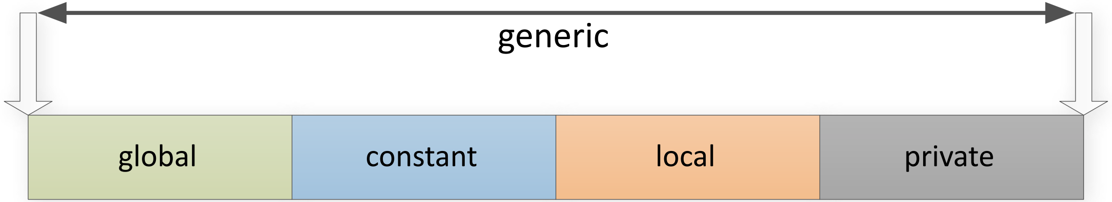
$$\text{constant} \overset{\cup}{\sim} \text{global}$$

is not valid…

GENERIC ADDRESS SPACE

Introduce an address space, *generic*, that subsumes all others

GENERIC ADDRESS SPACE



SCALE DEFINED IN TERMS OF GENERIC

```
int scale(generic int * A, generic int * B);
```

GENERIC BECOMES THE DEFAULT ADDRESS SPACE

```
int scale(int * A, int * B);
```

DOES GENERIC REQUIRE HARDWARE SUPPORT?

OpenCL C + generic

```
global int * g_ptr;
int x = *g_ptr;

int * ptr = g_ptr;
x = *ptr;

local int * l_ptr;
 x = *l_ptr;

g_ptr = l_ptr;
x = *g_ptr;
```

Pseudo IR + generic

```
int * g_ptr __attribute__(global)
int * ptr __attribute__(generic)
int * l_ptr __attribute(local)
int x;

x = load_global(g_ptr);
ptr = g_ptr;
x = load_generic(g_ptr); // global mem load

x = load_local(l_ptr);
g_ptr = l_ptr;
x = load_generic(g_ptr); // local mem load
```

CAN'T THE COMPILER DEDUCE WHAT TYPE OF LOAD GENERIC IS PERFORMING?

Maybe using Hidley-Milner type inference [1,2]?

SADLY

In general it is not possible!

EXAMPLE WHY HIDLEY-MILNER FAILS

```
void foo(int *);
kernel void bar(global int *g, local int *l)
{
   generic int * tmp;
   if (get_global_id(0) % 2) {
      tmp = g;
   } else {
      tmp = l;
   }
  foo(tmp);
}
```

GENERICS CAN BE MULTIPLE THINGS AT THE SAME TIME!

tmp is global and local for different work-items at the point foo(tmp)

GENERICS ARE VARIANT (OR SUM) TYPES

global + local int *

HOWEVER NOTE - FOR A GIVEN WORK-ITEM

A pointer instance within the generic address space can only point to one disjoint address space:

global
constant
local
private

at any given time.

THIS PAPER

Describes a type system that:

- combines the parametric polymorphism of generics
- with variant address spaces

- defines a type-inference algorithm that can infer parametric polymorphic variant address spaces types, for all valid programs, or fails

- defines a runtime implementation for generic address:
  - zero overhead for targets with hardware support for generic
  - overhead only in the presence of indirect functions with generic arguments

QUALIFIED TYPES

Our system is based on the general theory of qualified types [3]

Extended with the notion of variants [4]

Originally developed in the context of Haskell

```
class Eq a where
   (==) :: a -> a -> a

instance Eq Int where
   x == y = eqInt x y
```

```
(==) : forall a . Eq a => a -> a -> a

eqInt : Int -> Int -> Int
```

ADDRESS SPACE ARE DEFINED IN TERMS OF ROWS AND A CONSTRUCTOR

$$\{a_1, \ldots, a_n \mid r\} = \{a_1 \mid \ldots \{ a_n \mid r \} \ldots \}$$

$$\{a_1 , \ldots, a_n \} = \{a_1 \mid \ldots\{a_n \mid \{\}\}\ldots\}$$

A pointer of type τ in some address space a and some yet to be determined address spaces ranged over by r, is represented by the type:

$$\text{ASpace } \{a \mid r\}\ \tau *$$

DEFINITION (INJECTION) WITH INITIALIZER

Generic address space:

$\tau * x :: r => \text{size\_t} \rightarrow \text{Aspace}\ r\ \tau\ *$

int * x = 0xffffffff;

Disjoint address space a:

$a\ \tau * :: (r \setminus a) \Rightarrow \text{size\_t} \rightarrow \text{Aspace}\ \{a \mid r\}\ \tau\ *$

global int * x = NULL;

ASSIGNMENT (INJECTION)

$$
\_ = \_ :: (r \setminus a) \Rightarrow \text{Aspace}\ \{\ a \mid r\ \}\ \tau * \\
\rightarrow \text{Aspace}\ \{\ a \mid r\ \}\ \tau * \\
\rightarrow \text{Aspace}\ \{\ a \mid r\ \}\ \tau *
$$

```
global int * g_ptr; // disjoint definition (injection)
int * g;              // generic definition (injection)
int * ptr = g_ptr;   // assignment (injection)
```

ASSIGNMENT (EMBEDDING)

$$
\begin{aligned}
\_ = \_ :: (r \setminus a\ ) \Rightarrow \text{Aspace } r\ \tau * \\
\rightarrow \text{ASpace}\{a \mid r\ \}\ \tau * \\
\rightarrow \text{ASpace}\{\ a \mid r\ \}\ \tau *
\end{aligned}
$$

```
global int * g_ptr; // disjoint definition (injection)
local int * l_ptr;    // disjoint definition (injection)
int * ptr;            // generic definition (injection)

if (…) {
    ptr = g_ptr;      // assignment (embedding)
} else {
    ptr = l_ptr;      // assignment (embedding)
}
```

LOAD (STORE IS SIMILAR)

$$\mathrm{ld}(\_) :: (\{\} \setminus a) \Rightarrow \mathrm{ASpace}\{\ a\ \}\ \tau * \rightarrow \tau$$

$$\mathrm{ld}_a(\_,\_) :: (r \setminus a) \Rightarrow (\mathrm{ASpace}\{\ a\ \}\ \tau * \rightarrow \tau) \rightarrow \mathrm{ASpace}\{\ a \mid r\ \}\ \tau \rightarrow \tau$$

$$\begin{aligned}\mathrm{ld}(\_,\_,\_,\_) :: r \setminus a => {} & (\mathrm{ASpace}\{\ \mathrm{global}\}\ \tau * \rightarrow \tau\ ) \\ & \rightarrow (\mathrm{ASpace}\{\mathrm{local}\}\ \tau * \rightarrow \tau\ ) \rightarrow \\ & (\mathrm{ASpace}\{\mathrm{private}\}\ \tau * \rightarrow \tau\ ) \rightarrow \\ & \mathrm{ASpace}\ \{\ r \mid a\ \}\ \tau * \\ & \rightarrow \tau\end{aligned}$$

EXAMPLE

```
kernel void x(
   global * int g,
   local * int l,
   int value)
{
     int * var = 0;
     if (value % 2) {
        var = g;
     } else {
        var = l;
     }
      *g = *var;
}
```

```
kernel void x(
   ASpace { global } * int g,
   ASpace { local } * int l,
   int value)
{
     ASpace r int * var = 0;
     if (value % 2) {
        var = g;
     } else {
        var = l;
     }
     store_global(g,
          ld(var, ld_global, ld_local, ld_private));
}
```

THE DETAILS

The paper provides details of

1. the type inference algorithm

2. how predicates are used as ‘evidence’ to determine the address for a particular instance of a value within the generic address space domain

CONCLUSION

Formalized the notion of generic address spaces for OpenCL, Cuda, etc.

Naturally extends to languages such as C++

- As seen in the earlier OpenCL C++ paper

Formalizes Embedded C’s notion of generic address space

- Provides the ability to extend embedded C to C++

Type inference algorithm has potentially many other applications:

- e.g. scalar/vector usage of OpenCL C programs

REFERENCES

[1] J. R. Hindley. The principal type scheme of an object in combinatory logic. Transactions of the American Mathematical Society, 146:29–60, December 1969.

[2] R. Milner. A theory of type polymorphism in programming. Journal of Computer and System Sciences, August 1978.

[3] M. P. Jones. Qualified Types Theory and Practice. Distinguished Dissertations in Computer Science. Cambridge University Press, 1994.

[4] Benedict R. Gaster. *Records, variants, and qualified types*. PhD thesis, University of Nottingham, August 1998.