UNIVERSITY OF TWENTE.

VERIFICATION OF CONCURRENT AND DISTRIBUTED SOFTWARE

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SEVENTH FRAMEWORK PROGRAMME

erc

European Research Council

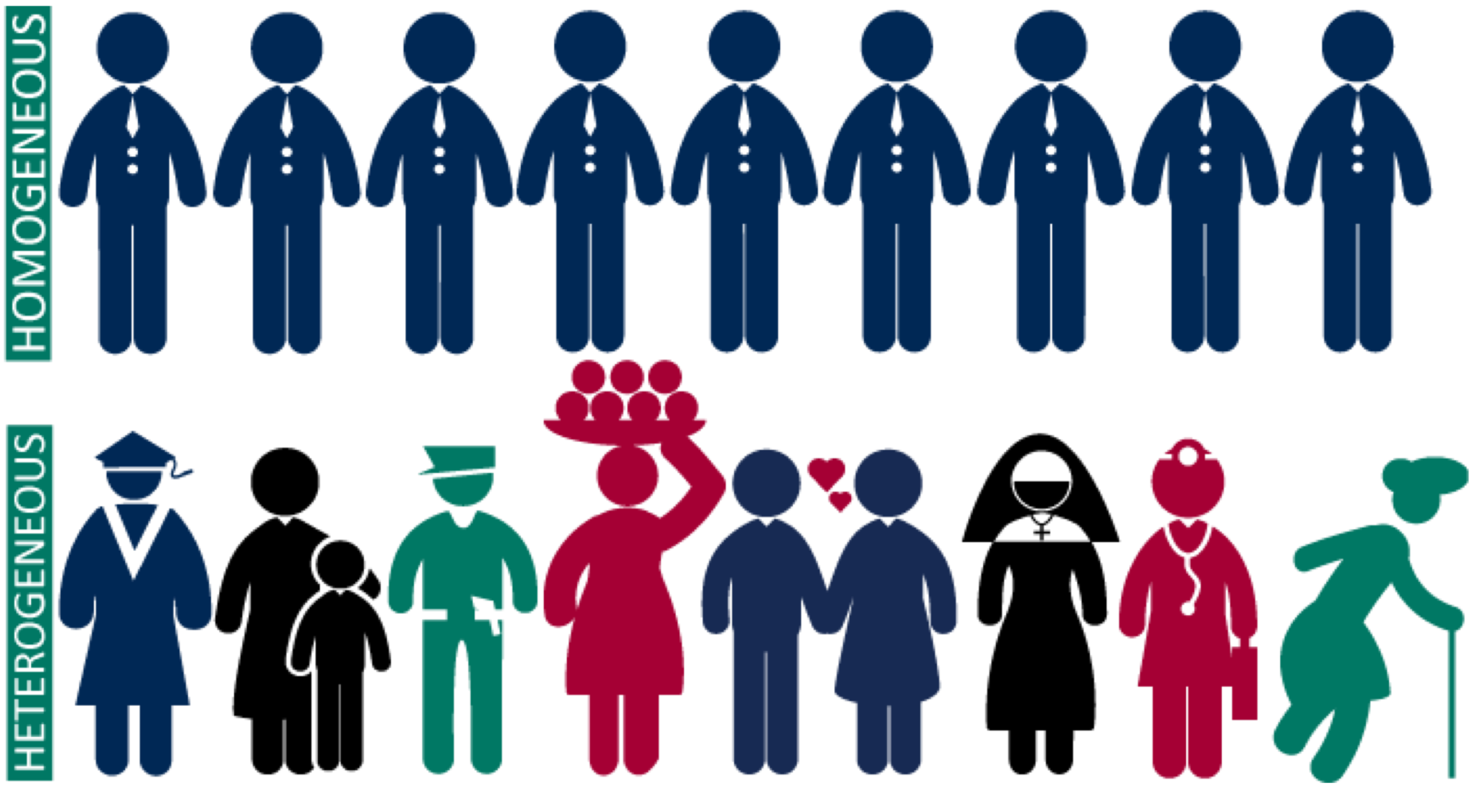
Established by the European Commission

OUTLINE OF THIS LECTURE

- How to ensure software quality?
- Classical program logic
- VerCors exercise
- The next challenge: concurrent software
- Permission-based separation logic
- VerCors exercise

- Reasoning about parallel blocks
- Verification of GPU kernels
- VerCors exercise
- Advanced verification features

HETEROGENEOUS VS HOMOGENEOUS THREADING



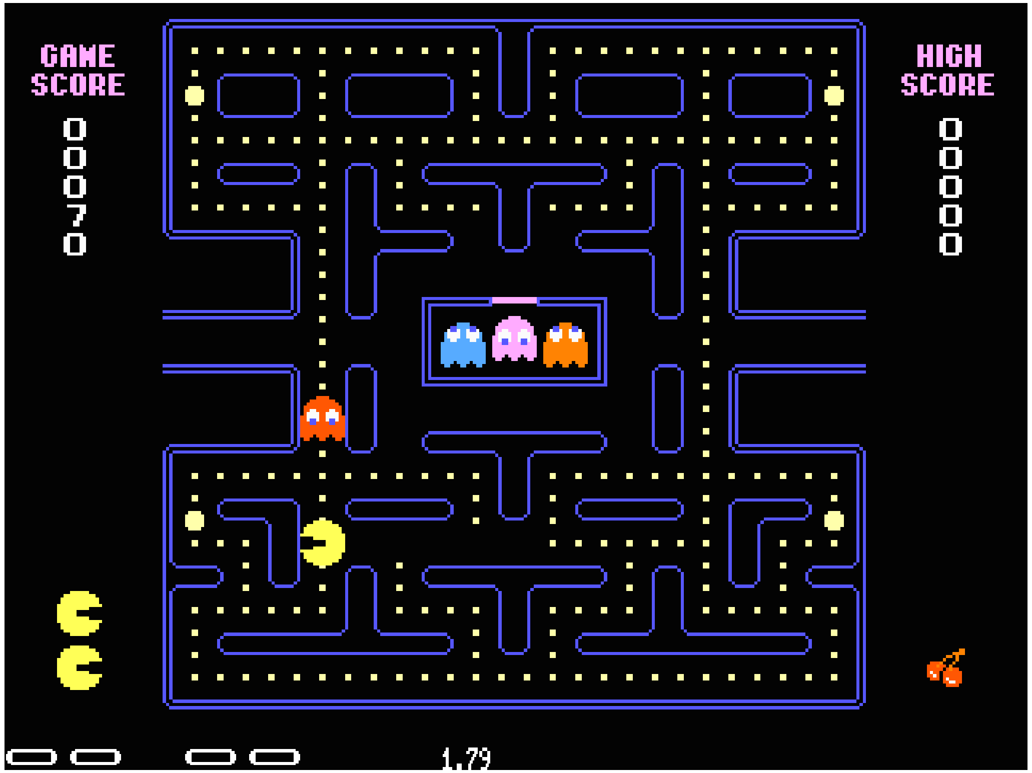
HETEROGENEOUS THREADING

- Every thread executes its own program
- Threads share data
- Efficiency achieved by smart division of tasks

HOMOGENEOUS THREADING

- Each thread executes same sequence of instructions
- Threads share data
- Typically, each thread accesses it own part of the data (otherwise: data race)
- Efficiency achieved by parallel execution of same job

GPU PROGRAMMING



GPU ARCHITECTURE

- Wikipedia:

  A graphics processing unit (GPU),

  also occasionally called visual processing unit (VPU),

  is a specialized electronic circuit designed to rapidly manipulate and alter memory to accelerate the building of images in a frame buffer intended for output to a display.

- SIMD architecture: built-in support for homogeneous threading
- Also useful for general purpose applications

GPU PROGRAMMING MODELS

- Cuda
  - NVIDIA-only
  - First
  - Widely-used
- OpenCL
  - Platform-independent
  - Can even run on CPU
  - Gaining interest

Essentially: an extended subset of C

EXAMPLE: ADDITION OF TWO VECTORS

Sequential program:

```
void vector_add(int size, float* a, float* b, float* c {
    for(int index = 0; index < size; index++) {
        c[index] = a[index] + b[index];
    }
}
```

VECTOR ADDITION AS OPENCL KERNEL

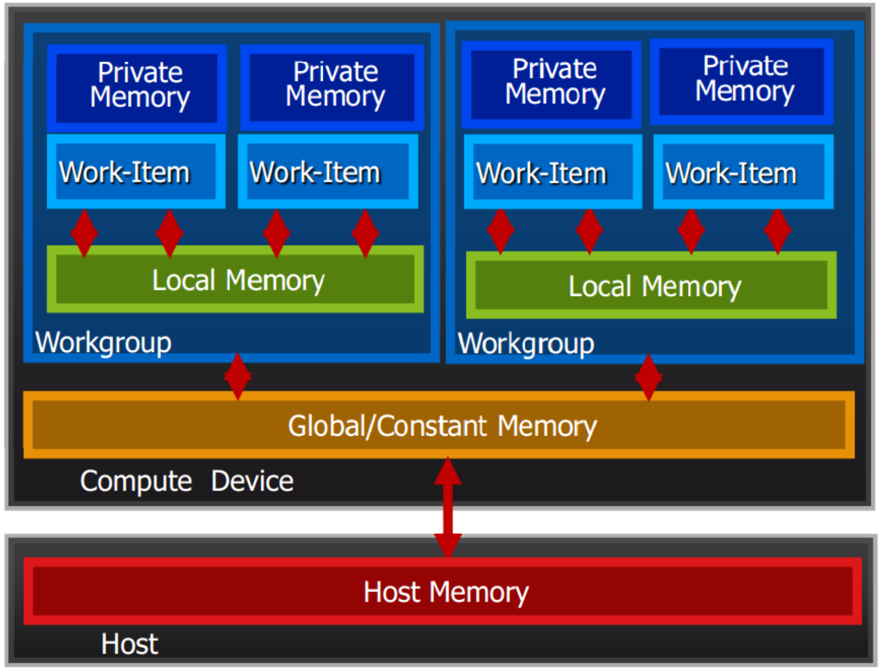
```
__kernel void vectorAdd(__global float* a,
                        __global float* b,
                        __global float* c) {
    int index = get_global_id(0);
    c[index] = a[index] + b[index];
}
```

__global
Where are the arrays stored

MULTIPLE MEMORY SCOPES

Beware for terminology:
- Local memory is shared by multiple work items (threads)
- Private memory is private to a single thread

- Per-thread private memory
- Per-workgroup shared memory
  - Low latency
- Global device memory (and constant memory)
  - Slower access
  - Can be accessed by any thread in any workgroup



Explicit copying between local and global memory

HIERARCHY OF CONCURRENT THREADS

- Parallel kernels composed of many threads
  - All threads execute the same sequential program
  - Called the kernel
- Threads (work items) are grouped into thread blocks (working group)
  - Threads in the same block can cooperate
  - Threads in different blocks cannot!

Thread identifiers typically determine which data is accessed

- Each thread has:
  - Local identifier: thread number in thread block
  - Global identifier: thread number in kernel

    Derived from local identifier and working group identifier

REASONING ABOUT KERNEL CODE

```
__kernel bla (__global float* a) {
    int tid = get_global_id(0);
    if (tid > 0) {
        a[tid] = a[tid] + a[tid – 1];
    }
}
```

What will happen here?

Data races should be avoided
Synchronisation needed
Solution: insert a barrier between the two assignments

REASONING ABOUT KERNEL CODE

```
__kernel bla (__global float* a) {
    int tid = get_global_id(0);
    int tmp = a[tid];
    if (tid > 0) {
        tmp = a[tid] + a[tid – 1];
    }
    BARRIER(CLK_GLOBAL_MEM_FENCE);
    a[tid]  = tmp;
}
```

SYNCHRONISATION WITHIN A KERNEL

- Barrier: all threads within a work group block until all threads have reached (the same) barrier
- This is the only moment where you can make an assumption about the state of another thread
- Barriers can be flagged with empty, local, global or local & global
  - Flag indicates which memory is synchronised when all threads reach the barrier

REDUCTION PATTERS AS KERNELS

Could we turn this into a kernel?

```
for (i=0; i<n; i++)
    sum += a[i];
```

We need a way to ensure that each thread does an atomic update

```
__kernel(__global float* a, __global int sum) {
    int tid = get_global_id(0);
    atomic_add(sum,a[tid]);
}
```

A LOGIC FOR GPU KERNELS

- Kernel specification
  - All permissions that a kernel needs for its execution
  - Separated in permissions for
    - Global Memory – given up by host code
    - Shared Memory – local to the GPU
- Thread specification
  - Permissions needed by single thread
  - Should be a subset of kernel permissions
- Barrier specification
  - Each barrier allows redistribution of permissions

Actually:
Group specification in between kernel and thread specification

Plus: functional specifications (pre- and postconditions)

EXAMPLE SPECIFICATION

```
_kernel void bla( _global float* input,
                  _global float* output) {
  int i = get_global_id(0);
  output[i] = input[i] * input[i];
  barrier(CLK_GLOBAL_MEM_FENCE);
  output[(i+1)%wg_size]=
        output[(i+1)%wg_size] * input[i];
}
```

Provided by host

Kernel Specification:

Global Memory Resources:

(forall∗ int i; 0 <= i < output.length; Perm(output[i], 1)

(forall∗ int i; 0 <= i < input.length; Perm(input[i], ½)

Shared Memory Resources: -

Thread Specification:

Precondition:

Perm(output[tid], 1) ∗
Perm(input[tid], ½)

Postcondition:

Perm(output[(tid + 1) % wg_size], 1) ∗
Perm(input[tid], ¼) ∗ Perm(input[(tid + 1) % wg_size], ¼) ∗
output[(tid + 1) % wg_size] = input[tid] ∗ input[(tid + 1) % wg_size]^2

Global proof obligation:
All threads together use no more resources than available in the kernel

EXAMPLE
BARRIER SPECIFICATION

```
_kernel void bla( _global float* input,
                              _global float* output) {
   int i = get_global_id(0);
   output[i] = input[i] * input[i];
   barrier(CLK_GLOBAL_MEM_FENCE);
   output[(i+1)%wg_size]=
          output[(i+1)%wg_size] * input[i];
}
```

Barrier Specification:

Precondition:

Perm(output[tid], 1) ✳ Perm(input[tid], ½) ✳
output[tid] = input[tid] ✳ input[tid]

Postcondition:

Perm(output[(tid + 1) % wg_size], 1) ✳
Perm(input[tid], ¼) ✳ Perm(input[(tid + 1) % wg_size], ¼) ✳
output[(tid + 1)% wg_size] = input[(tid + 1)% wg_size]^2

Global proof obligation:
All permissions available in kernel

Global proof obligation:
Barriers correctly transfer knowledge about state

Extra layer:
workinggroup specifications

PROOF OBLIGATIONS

- Threads respect their thread specification
- Kernel resources are sufficient to provide each thread necessary global resources
- Local resources are properly distributed over threads
- Kernel precondition implies universal quantification of thread precondition
- Barriers only redistribute permissions that are in the kernel
- Universal quantification of barrier precondition implies universal quantification of barrier postcondition
- Universal quantification of thread postcondition implies kernel postcondition

PARALLEL BLOCK: VERCORS ENCODING

- OpenCL kernels encoded as sequences of parallel blocks

```
par (int tid = 0 .. A.length)
{
    A[tid] = 0;
}
```

- Each parallel block ends with an implicit barrier
- For more complicated patterns, also explicit barrier statement
- Each iteration in parallel block should be specified by pre- and postcondition
- Atomic operations:

```
atomic(inv) { critical section code }
```

where inv is the resource invariant that gives access to this code

EXERCISES

Code voor exercises and some examples available from
https://wwwhome.ewi.utwente.nl/~marieke/VTSA

TOWARDS THE FULL POWER OF VERIFICATION

- Abstract predicates: encapsulate state
- Ghost variables: verification-only state
- Abstract models to reason about functional behavior of concurrent programs

ABSTRACT PREDICATES

Matthew Parkinson

SPECIFYING DATA STRUCTURES

- Abstract predicates represent and encapsulate state, with appropriate operations
- Abstract predicates are scoped
  - Code verified in scope can use name and body
  - Code verified out of scope can only use name
- Explicit open/close axiom to open definition of abstract predicate, provided it is in scope

$$\alpha(x1, .., xn) = P \text{ in scope } \vdash \alpha(e1, .., en) \Leftrightarrow P[x1 := e1, .. xn := en]$$

ABSTRACT PREDICATES ON LIST

```
class Node {
        int val;
        Node next;
}
```

- Predicate list
  - pred list (i)= (i = null) $\vee$ $\exists$ Node j, int a. i.val $\rightarrow$ a $\ast$ i.next $\rightarrow$ j $\ast$ list j

  recognises list structure
- Predicate list:
  - pred list (ϵ, i) = (i = null)
  - pred list ((a.α), i) = $\exists$Node j. i.val $\rightarrow$ a $\ast$ i.next $\rightarrow$ j $\ast$ list α j

  relates list content with abstract list value
- Operations like append and reverse in specifications can be defined on abstract type

LIST PREDICATE IN VERCORS

```
class Node {

  int value;
  Node next;

  resource list(frac p) =
     p != none ** Perm(value, p) ** Perm(next, p) **
     (next != null ==> next.list(p));

}
```

GHOST VARIABLES

- Sometimes verification requires to maintain extra state: ghost state
- Examples:
  - Keep track of original variables
  - Keep track how variables evolve
  - Compute additional properties over state

- VerCors approach:
  - given T v : pass extra ghost parameter v of type T to method
  - yields T v: method returns an extra ghost return value
  - m() with {givenvar = E} then {z = yieldsvar}

EXAMPLE GHOST TRACE

```
function up-sweep(int H, int N, seq<int[]> Tree, seq<int> Input, int tid) {
    int lvl=1;
    while (lvl ≤ H) {
        if (lvl < N/2) {
            a[tid] = a[2 * tid] + a[2 * tid + 1];
            Tree[lvl][tid] = Tree[lvl - 1][2 * tid] + Tree[lvl - 1][2 * tid + 1];
            barrier(tid);
            lvl = lvl + 1;
        }
    }
}
```

FUNCTIONAL VERIFICATION OF CONCURRENT PROGRAMS

Wytse Oortwijn

Marina Zaharieva – Stojanovski

EXAMPLE: PARALLEL INCREASE

How to prove:

Ghost code solution:

```
                {x = a + b & a == 0 & b == 0}
{x == a + b & a == 0}        || {x == a + b & b == 0}
<x := x + 1;>                || <x := x + 1;>
<a := 1;> // ghost           || <b :=1;> //ghost
{x == a + b & a == 1}        || {x == a + b & b == 1}
                {x == a + b & a == 1 & b == 1}
                          {x == 2}
```

Problem:

```
{x == 0}
< x := x + 1;>
{x == 1}
```

Our approach:
Maintain abstract model of updates

unstable: assertions can be made invalid by other threads

AS A JAVA-LIKE PROGRAM

```
class Counter{
    int data;
    Lock l;
    resource_inv = exists v. PointsTo(x, 1, v);

requires true;
ensures  true;
void increase(){
    l.lock();          // obtain PointsTo(x, 1, v);
    x++;
    l.unlock();        // loose PointsTo(x, 1, v + 1);
    // now we don't know anything about x anymore
  }
}
```

Client:

```
c = new Counter(0);
fork t1;   //t1 calls c.increase();
fork t2;   //t2 calls c.increase();
join t1;
join t2;

// Is  c.x  == 2 ?
```

Permission to read and update x

Needed:
A specification of increase that indicates what behavior of increase is

A HISTORY OF ACTIONS

Abstract model is process algebra term composed of user-defined actions (use ACP)

Examples

```
action a<int x>(int k) = \old(x) + k;

action b<list l>(int e) = cons(\old(l), e);

action c<int k>(int w) = w;
```

COUNTER SPECIFICATION

```
class Counter{
   int data;
   Lock l;
    //resource_inv = Perm(x, 1);

    //action a<int x> () = \old(x) + 1;

requires Model(x, p, M.a);
ensures Model(x, p, M);
void increase(){
    l.lock();  /* start a */ x++; /* record a */ l.unlock();
    }
}
```

Record LOCAL changes in the history

EXAMPLE: OWICKI GRIES

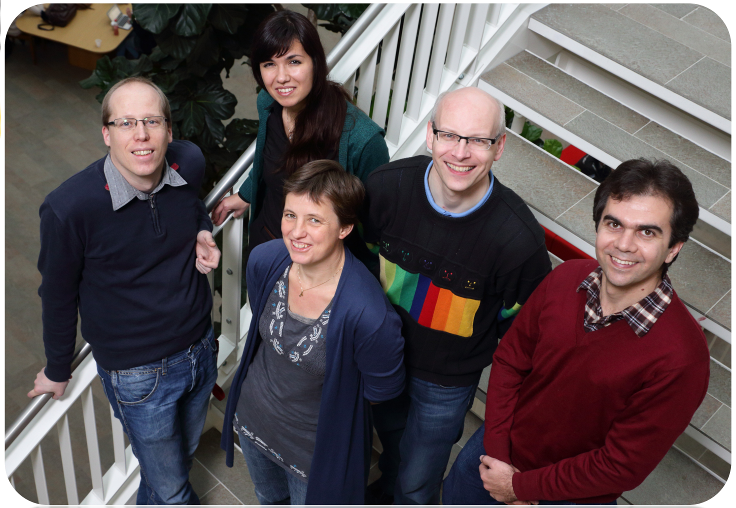
```
class Future {
    int x;

    modifies x;
    ensures x == \old(x) + 2;
    process incr();

    modifies x;
    ensures x == \old(x) + 4;
    process OG() = incr() || incr();
}
```

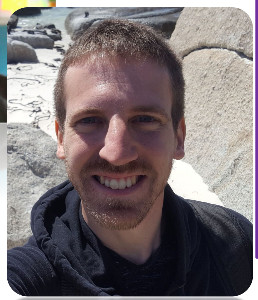
OWICKI GRIES PROGRAM

```
ensures \result == x + 4;
int main(int x) {
    model.x = x;
    invariant inv(HPerm(model.x, 1)) //;
    {
        par Thread1()
        { atomic (inv) { model.x = model.x + 2; } }
        and Thread2()
        { atomic (inv) { model.x = model.x + 2; } }
    return model.x;
}
```

For the annotations, we go to my editor

ACKNOWLEDGEMENTS





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Sebastiaan Joosten, Mohsen Safari, Fauzia Ehsan,
Raul Monti, Henk Mulder, Pieter Bos, Jelte Zeilstra

EXERCISES

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