31st ACM/SIGAPP Symposium on Applied Computing

SMT-Based Context-Bounded Model Checking for CUDA Programs

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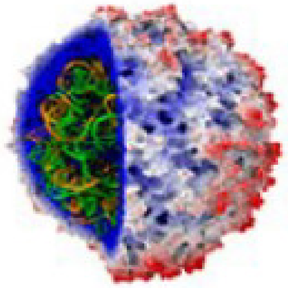
Isabela Silva, Vanessa Santos, Celso Barbosa, Ricardo
Ferreira, and **Lucas Cordeiro**

CUDA: parallel computing platform and API model

- Developed by NVIDIA to configure GPUs



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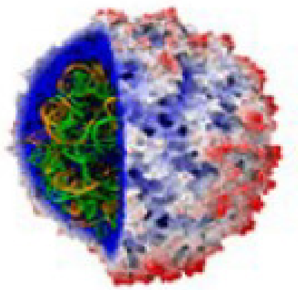

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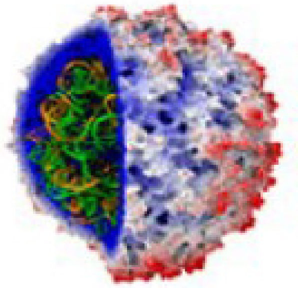

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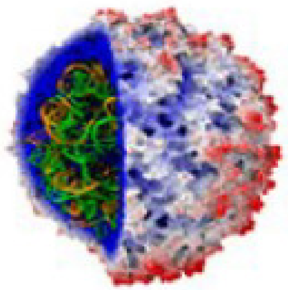
- We need to ensure **code correctness** in safety-critical GPU applications



Typical Programming Errors in CUDA

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Array out-of-bounds due to incorrect access in unallocated memory region

```
int a[2];
...
kernel(int *a){
    if(a[1]==1)
        a[threadIdx.x+2] = threadIdx.x ;
    else
        a[threadIdx.x] = threadIdx.x;
}
```

Objectives of this work

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- Apply **context-bounded model checking** based on the Satisfiability Modulo Theories (SMT)
  - Monotonic Partial Order Reduction (MPOR) (CAV’09)

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- Apply **context-bounded model checking** based on the Satisfiability Modulo Theories (SMT)
  - Monotonic Partial Order Reduction (MPOR) (CAV’09)
- Compare **ESBMC-GPU** experimental results with other **state-of-art software verifiers** for CUDA

CUDA Operational Model (COM)

- COM aims to
  - **Abstractly** represent the associated CUDA libraries
    - checks **pre-** and **post-conditions**
    - simulates **behavior**
  - Reduce verification effort
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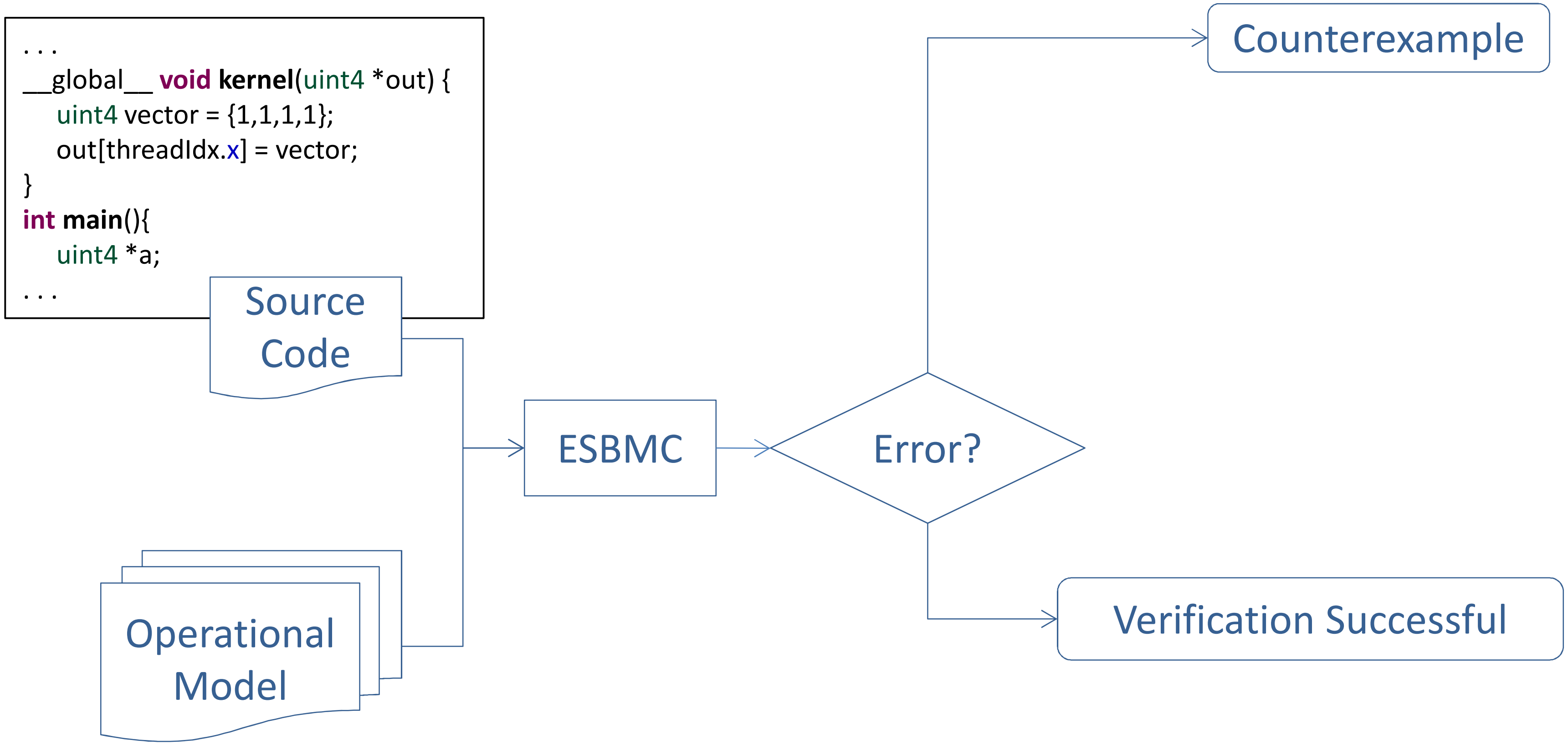
  - Other extensions to ESBMC based on operational models
    - ESBMC++ (ECBS'13) and ESBMC^{QtOM} (SPIN'16)
- CUDA is a **proprietary platform**
  - CUDA Programming Guide and IDE Nsight

ESBMC-GPU: Verification Flow



```
. . .
__global__ void kernel(uint4 *out) {
    uint4 vector = {1,1,1,1};
    out[threadIdx.x] = vector;
}
int main(){
    uint4 *a;
. . .
```

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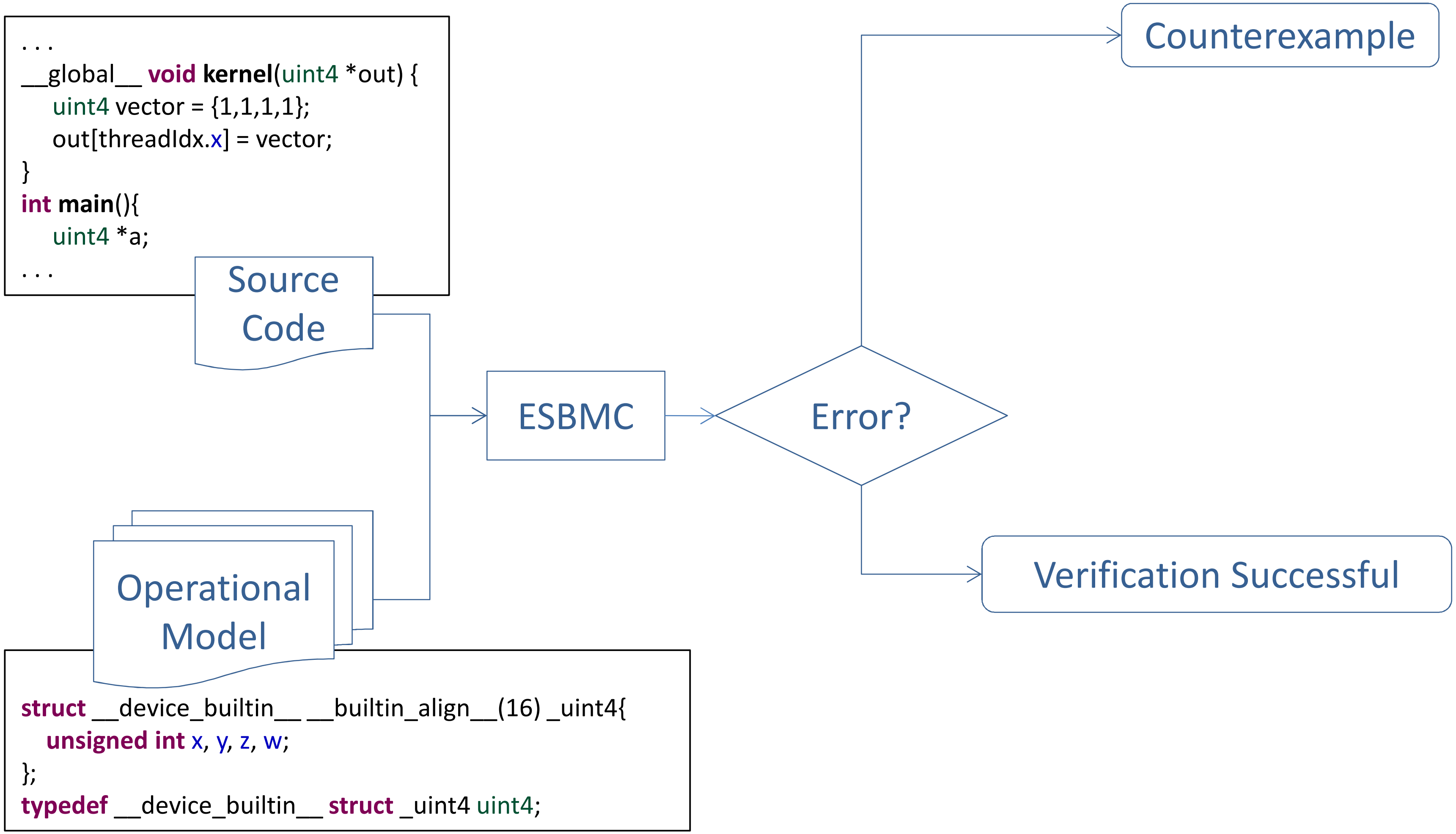

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```

Source Code

Operational Model

```
struct __device_builtin__ __builtin_align__(16) _uint4{
   unsigned int x, y, z, w;
};
typedef __device_builtin__ struct _uint4 uint4;
```

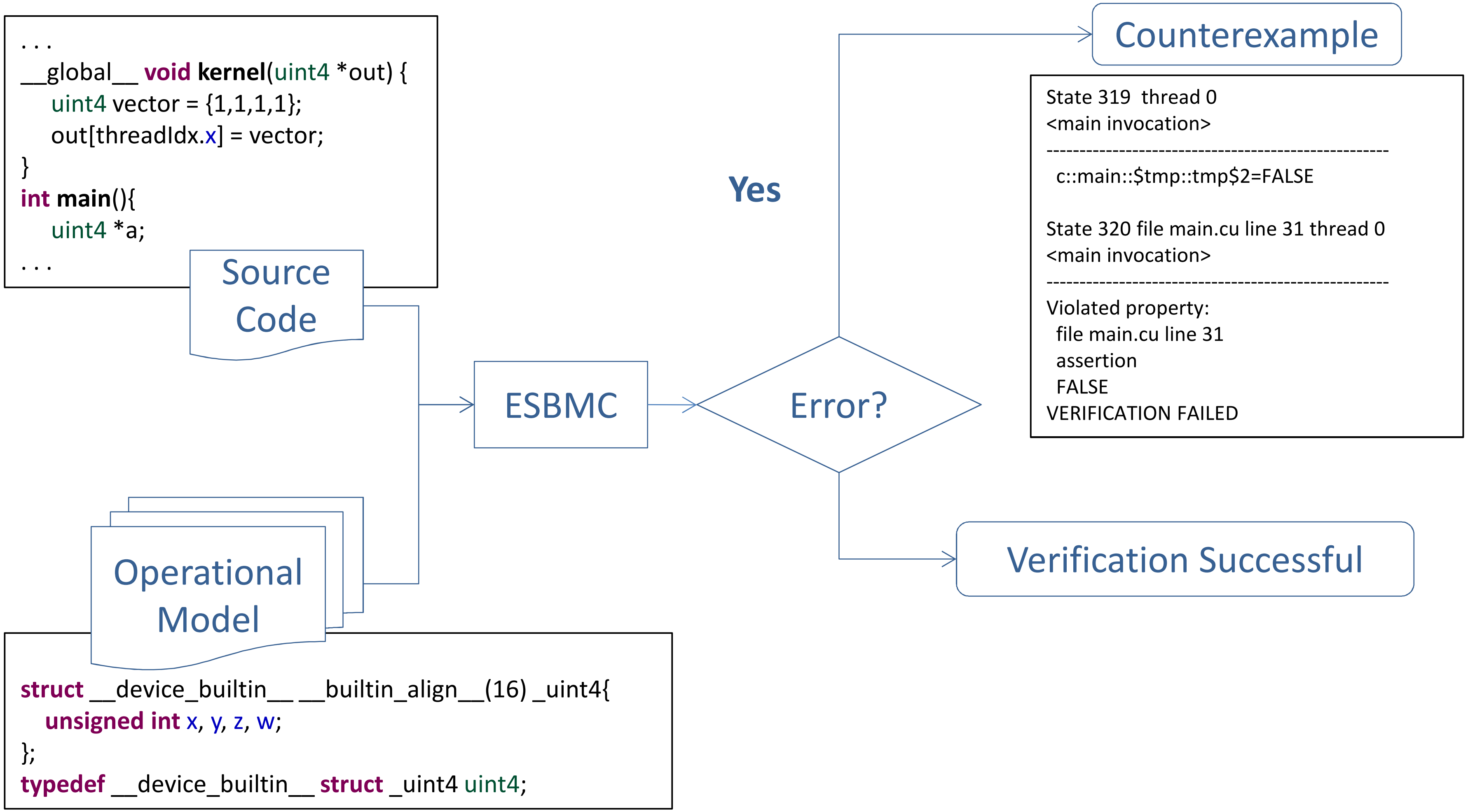
ESBMC

Error?

Counterexample

Verification Successful

ESBMC-GPU: Verification Flow



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ESBMC

Error?

Yes

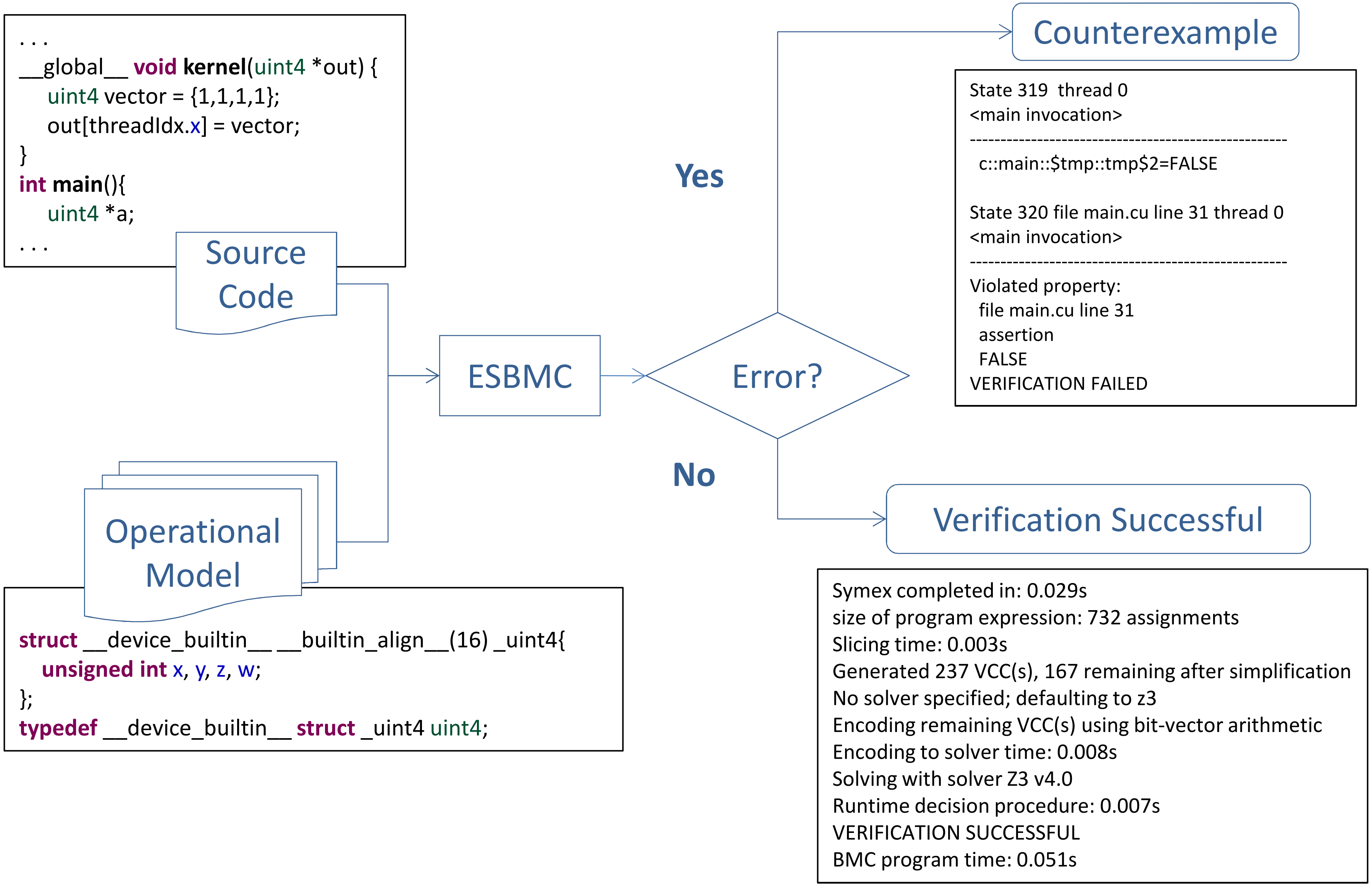
Counterexample

```
State 319  thread 0
<main invocation>
----------------------------------------------------
  c::main::$tmp::tmp$2=FALSE

State 320 file main.cu line 31 thread 0
<main invocation>
----------------------------------------------------
Violated property:
  file main.cu line 31
  assertion
  FALSE
VERIFICATION FAILED
```

Verification Successful

ESBMC-GPU: Verification Flow



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<main invocation>
----------------------------------------------------
Violated property:
  file main.cu line 31
  assertion
  FALSE
VERIFICATION FAILED
```

No

Verification Successful

```
Symex completed in: 0.029s
size of program expression: 732 assignments
Slicing time: 0.003s
Generated 237 VCC(s), 167 remaining after simplification
No solver specified; defaulting to z3
Encoding remaining VCC(s) using bit-vector arithmetic
Encoding to solver time: 0.008s
Solving with solver Z3 v4.0
Runtime decision procedure: 0.007s
VERIFICATION SUCCESSFUL
BMC program time: 0.051s
```

COM Implementation: *cudaMalloc*

```
#include <cuda.h>
#include <stdio.h>
 #define N 2
 __global__ void definitions(int* A){
            atomicAdd(A,10);
}
 int main (){
            int a = 5;
            int *dev_a;
            cudaMalloc ((void**) &dev_a, sizeof(int));
            cudaMemcpy(dev_a, &a,
sizeof(int),cudaMemcpyHostToDevice);
            ESBMC_verify_kernel(definitions,1,N,dev_a);
            cudaMemcpy(&a,dev_a,sizeof(int),cudaMemcpyD
eviceToHost);
            assert(a==25);
            cudaFree(dev_a);
            return 0;
}
```

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		return 0;
}
```

COM Implementation: *cudaMalloc*

```
# cudaMalloc
cudaError_t cudaMalloc(void ** devPtr, size_t size) {
        cudaError_t tmp;
        __ESBMC_assert(size > 0, "Size to be allocated must be greater than zero");
        *devPtr = malloc(size);
         if (*devPtr == NULL) {
                  tmp = CUDA_ERROR_OUT_OF_MEMORY;
                  exit(1);
          } else {
                  tmp = CUDA_SUCCESS;
          }
        __ESBMC_assert(tmp == CUDA_SUCCESS, "Memory was not allocated");
        lastError = tmp;
        return lastError;
}
```

pre-condition

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simulate behavior

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- Verification model adopts the CPU parallel processing
  - Using the Pthread/POSIX library

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CUDA program

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_global_ void kernel(){
  A[tidx.x]=tidx.x;
}

int main(){
  int *a; int *dev_a;
  cudaMalloc(&dev_a,a,size);
  ...
  cudaMemcpy(dev_a,a,htd);
  ...
  ESBMC _verify_kernel(
kernel,M,N,dev_a);
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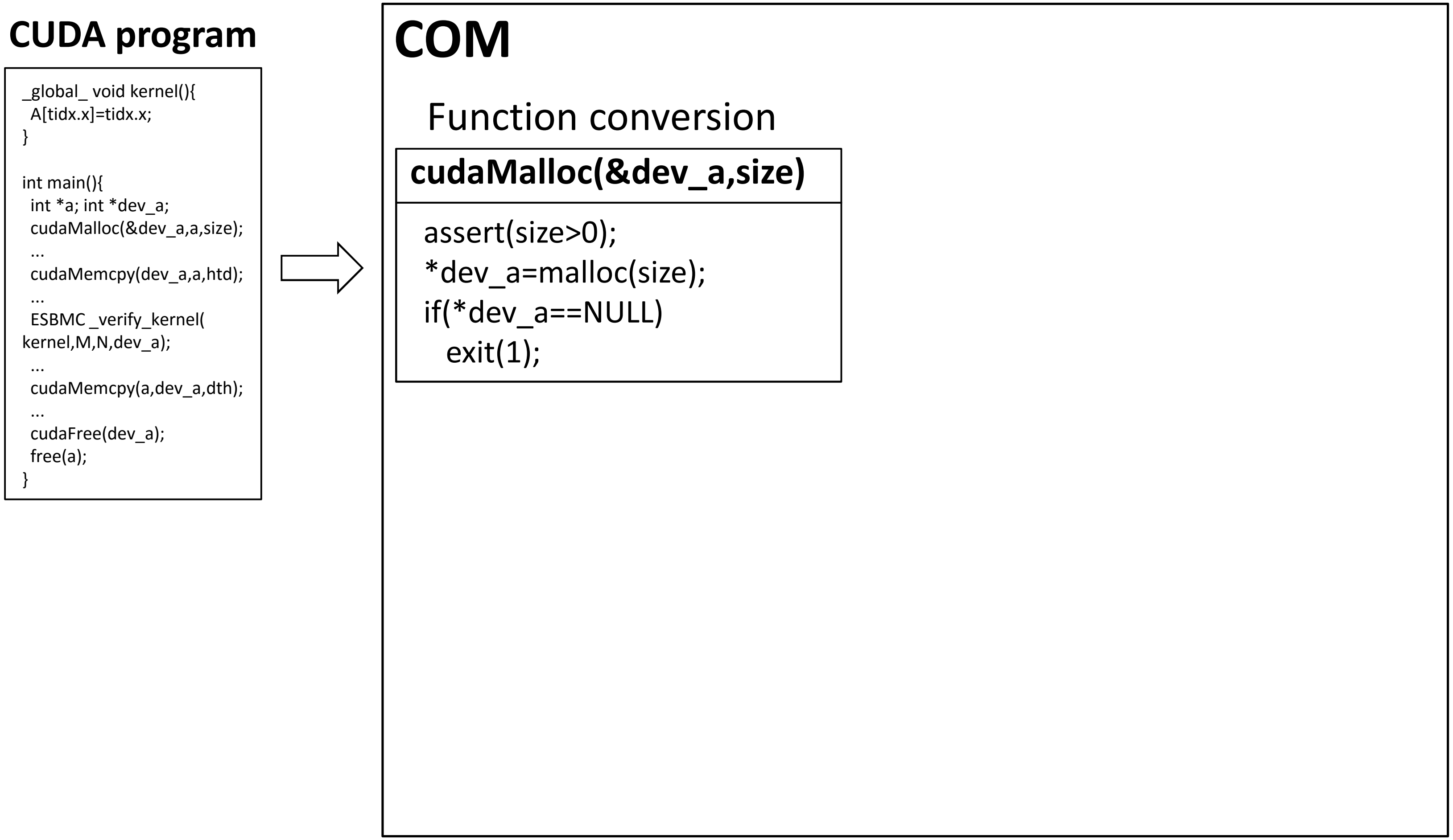

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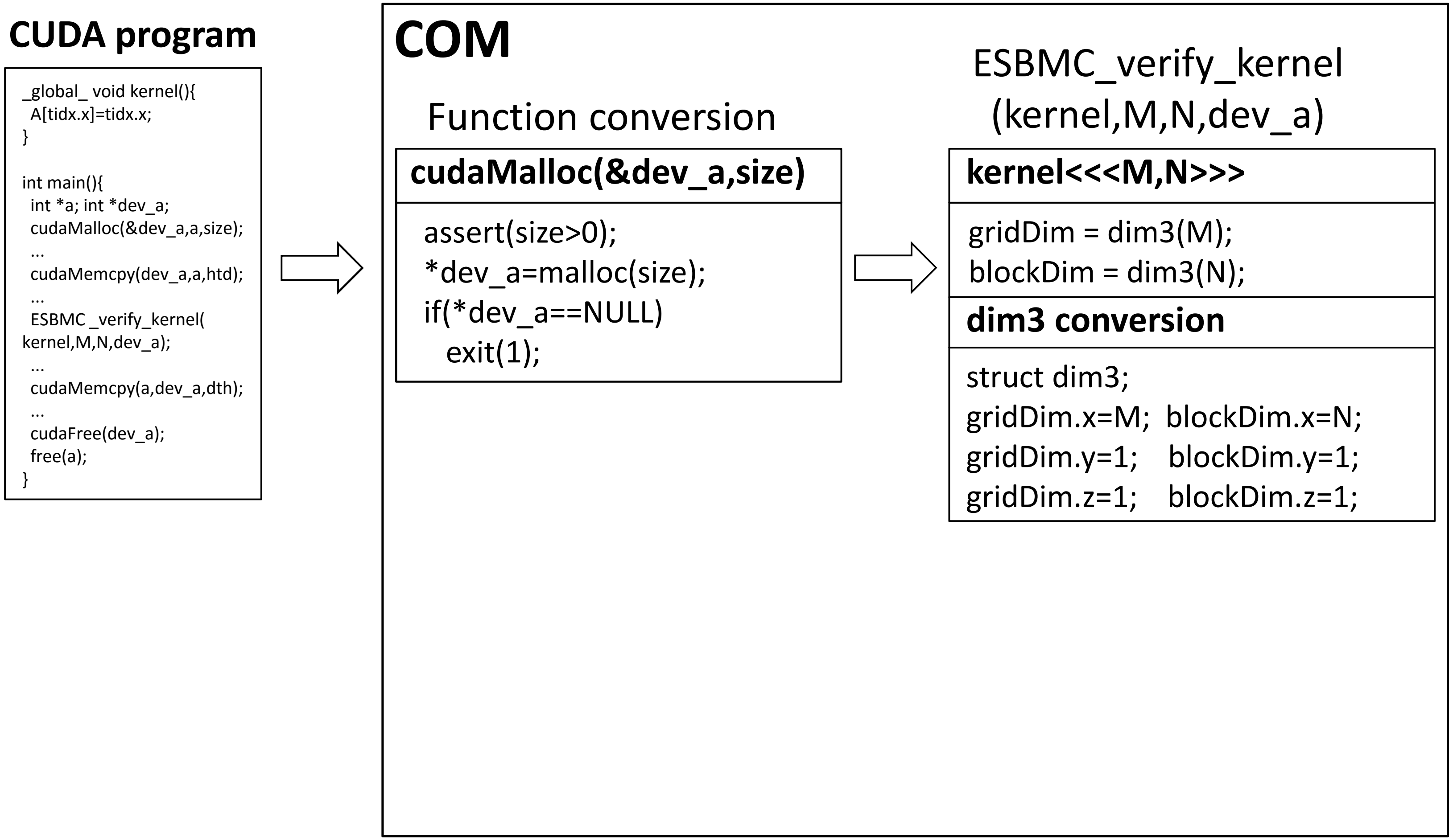

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ESBMC_verify_kernel
(kernel,M,N,dev_a)

kernel<<<M,N>>>

```
gridDim = dim3(M);
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dim3 conversion

```
struct dim3;
gridDim.x=M;  blockDim.x=N;
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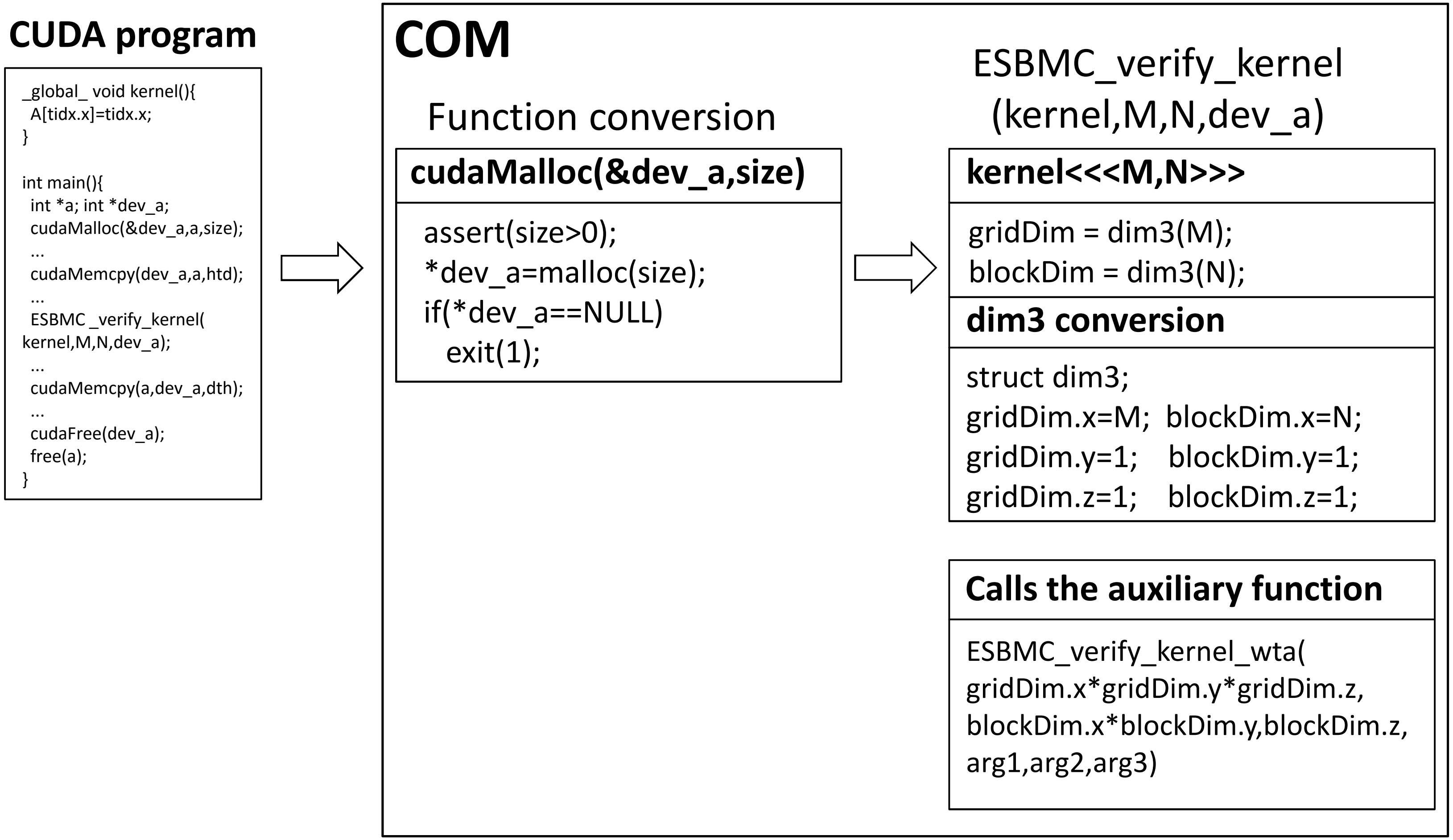

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Calls the auxiliary function

```
ESBMC_verify_kernel_wta(
gridDim.x*gridDim.y*gridDim.z,
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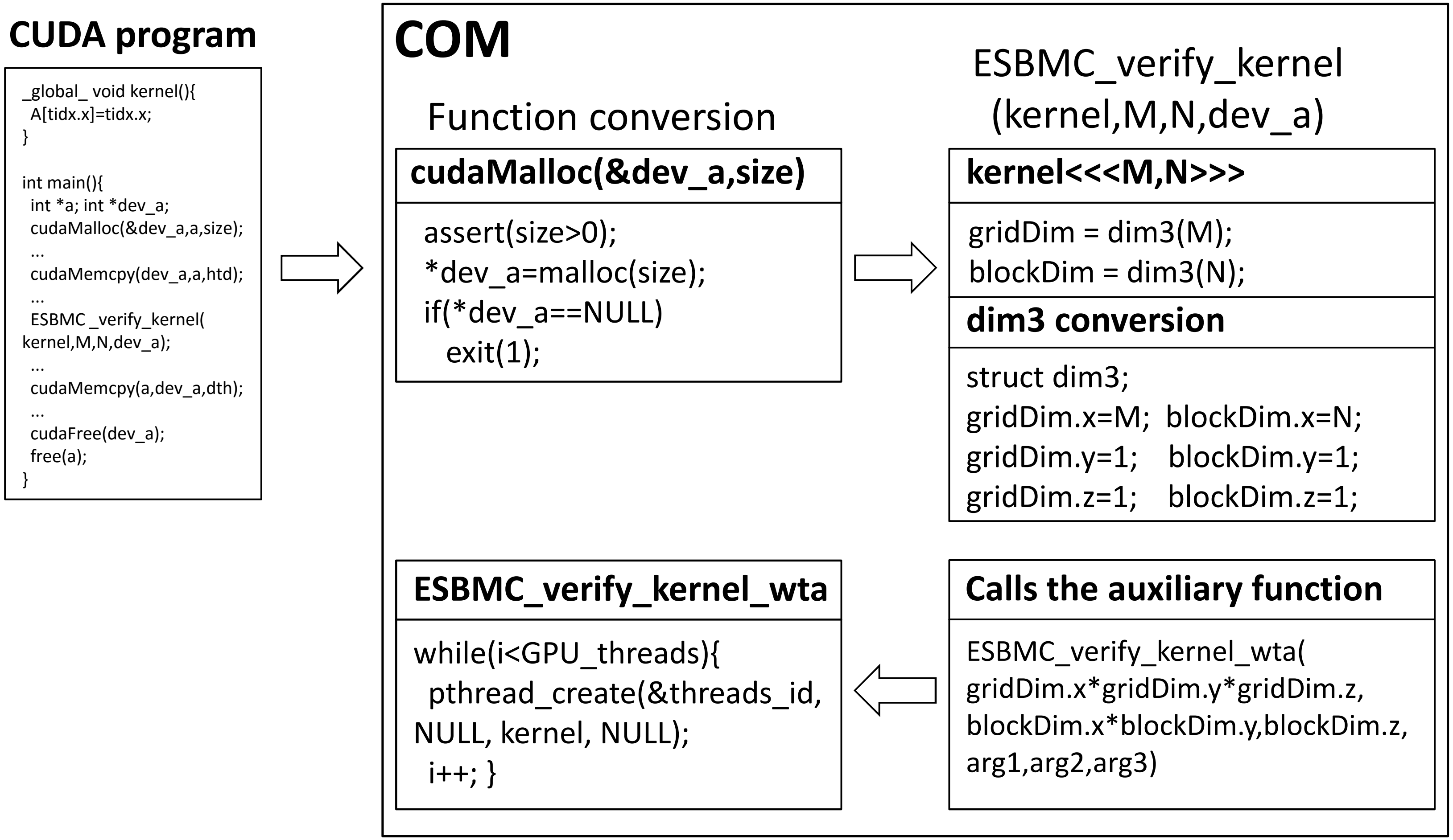

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ESBMC_verify_kernel_wta

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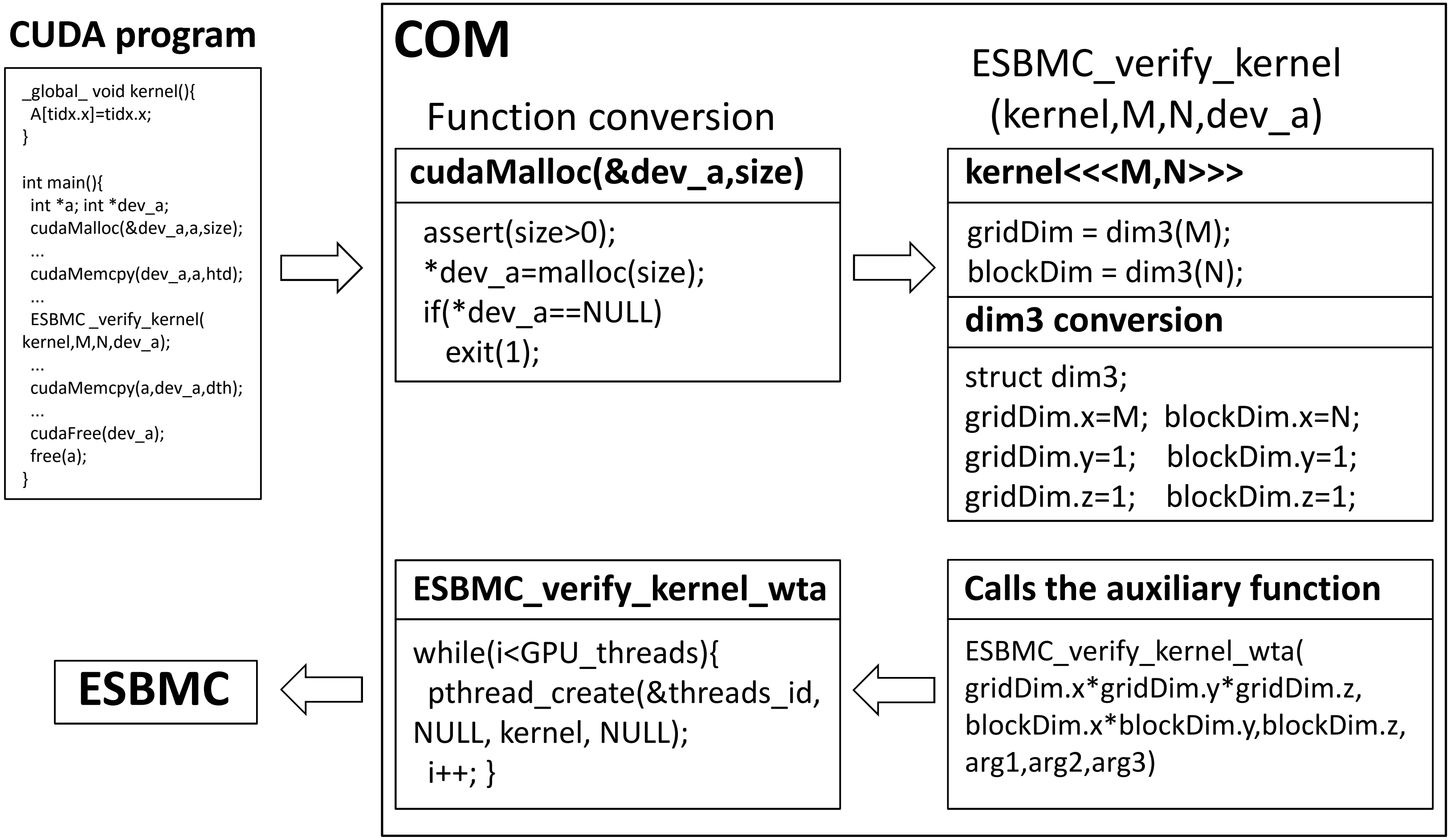

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ESBMC

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- MPOR classifies thread transitions in a multi-threaded program
  - Each transition may be dependent or independent
    - ➢Identify interleaving pairs which result in the same state
- First application of the technique to verify CUDA-based programs
  - Reduction in time and verification effort
  - Elimination of threads interleavings that **access different array positions**

MPOR Applied to CUDA-based Programs

- MPOR algorithm in the ESBMC-GPU

```
1.  function MPOR (v, π)
2.    Check whether $s_i$ exists in π; otherwise, go to step 4
3.    Check whether $A_i$ produces a new state in π; otherwise,  go to step 5
4.    Analyze whether $\gamma(s_{i-1}, s_i)$ is independent on π; otherwise, go to step 6
5.    Return “independent” on π and terminates
6.    Return “dependent” on π and terminates
7.  end function
```

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v = (A_i, C_i, s_i)
A_i: active thread
C_i: context switch
s_i: current state

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```
kernel1(int *a){
    a[threadIdx.x] = threadIdx.x ;
}
```

v_0: $t_0, 0, a[0] = 0\ , a[1] = 0$

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1. function MPOR (v, π)        $\pi = \{v_0, \dots, v_k\}$
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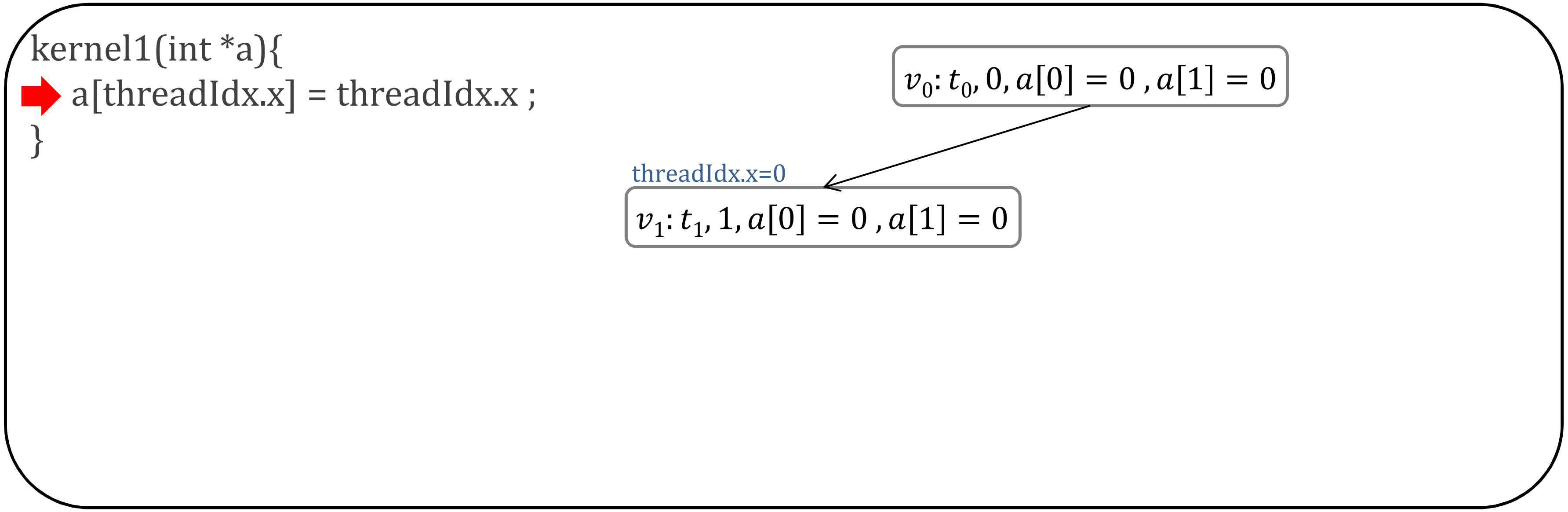
5.   Return "independent" on π and terminates
6.   Return "dependent" on π and terminates
7. end function
```



```
kernel1(int *a){
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}
```

MPOR Applied to CUDA-based Programs

- MPOR algorithm in the ESBMC-GPU

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A_i: active thread
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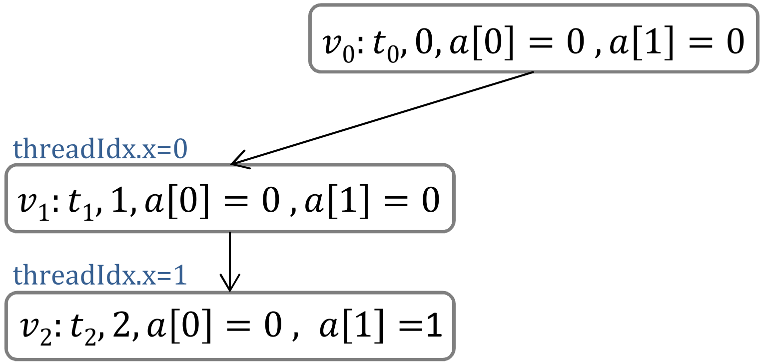

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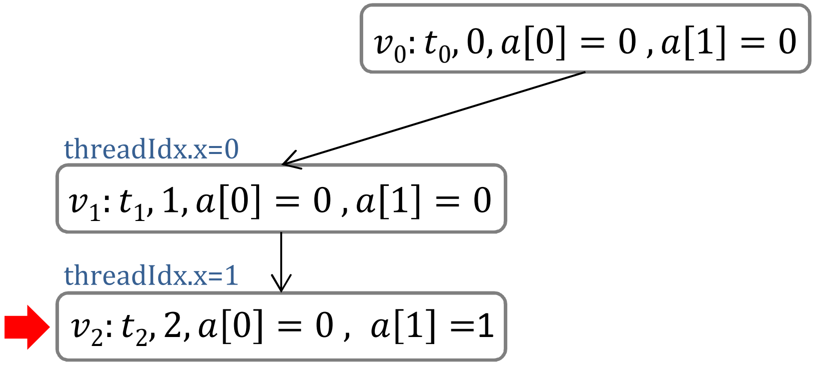

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- MPOR algorithm in the ESBMC-GPU

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```
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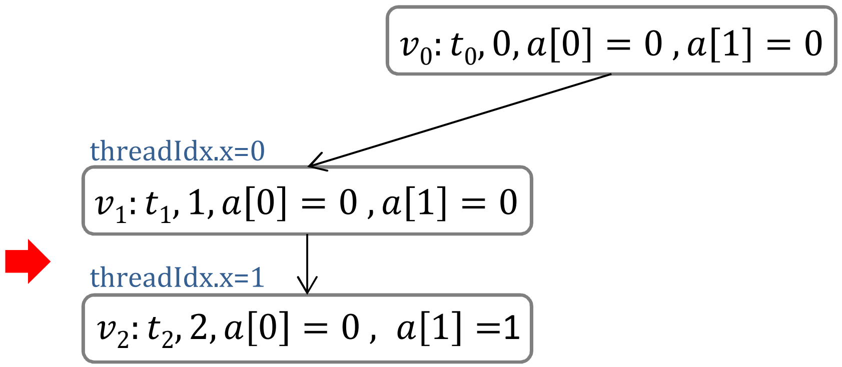
}
```

$t_1 \rightarrow t_2$
s_2: a[0] = 0
      a[1] = 1



$v_0: t_0, 0, a[0] = 0\,, a[1] = 0$

threadIdx.x=0

$v_1: t_1, 1, a[0] = 0\,, a[1] = 0$

threadIdx.x=1

$v_2: t_2, 2, a[0] = 0\,,\ a[1] = 1$

MPOR Applied to CUDA-based Programs

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}
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Dependent

$t_1 \rightarrow t_2$

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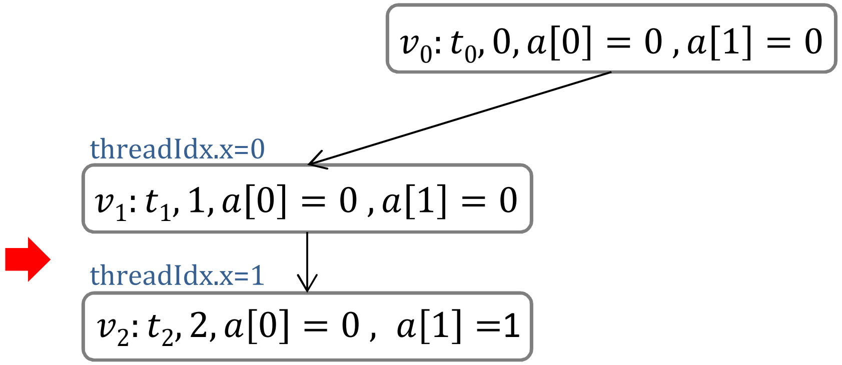

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threadIdx.x=0

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threadIdx.x=1

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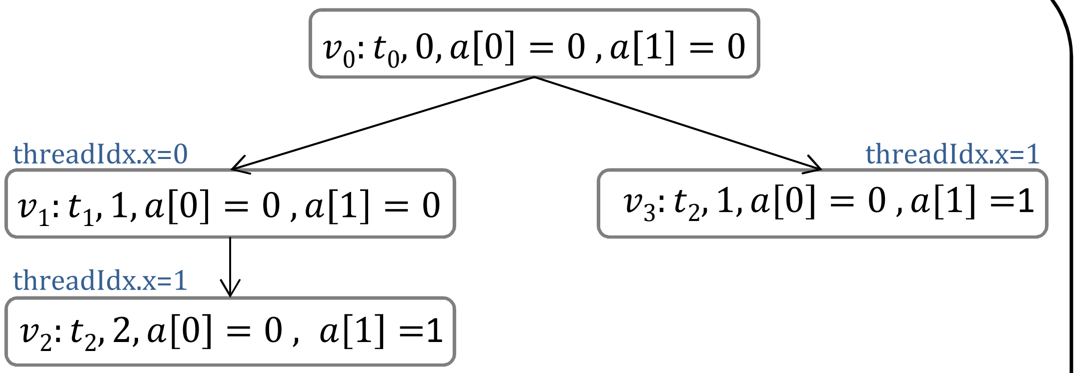

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threadIdx.x=0

$v_1: t_1, 1, a[0] = 0, a[1] = 0$

threadIdx.x=1

$v_2: t_2, 2, a[0] = 0, a[1] = 1$

threadIdx.x=1

$v_3: t_2, 1, a[0] = 0, a[1] = 1$

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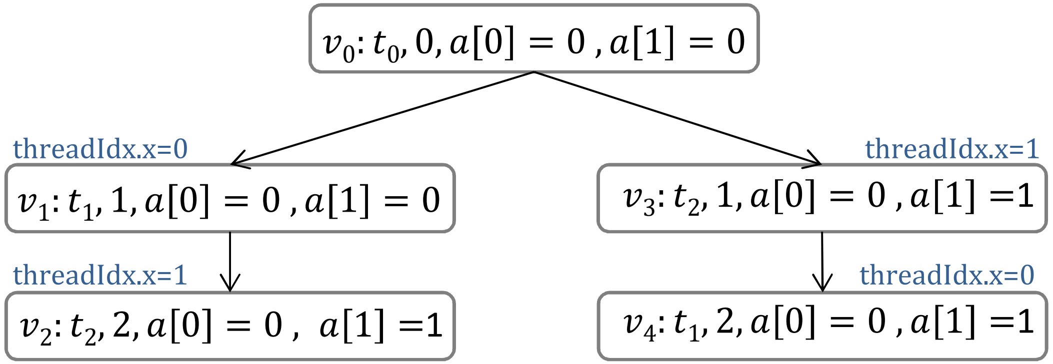

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threadIdx.x=0

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$v_2: t_2, 2, a[0] = 0, a[1] = 1$

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```
kernel1(int *a){
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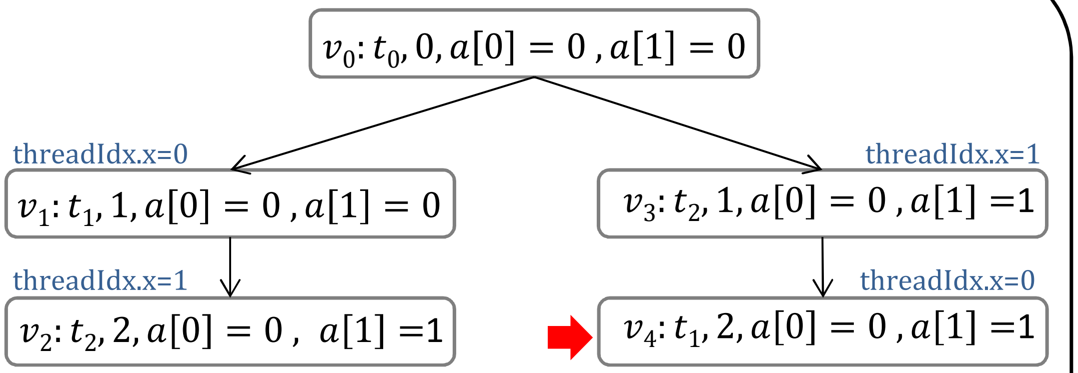
}
```

Dependent

$t_1 \rightarrow t_2$	$t_2 \rightarrow t_1$
s_2: a[0] = 0 a[1] = 1	s_2: a[0] = 0 a[1] = 1



$v_0: t_0, 0, a[0] = 0, a[1] = 0$

threadIdx.x=0

$v_1: t_1, 1, a[0] = 0, a[1] = 0$

threadIdx.x=1

$v_2: t_2, 2, a[0] = 0, a[1] = 1$

threadIdx.x=1

$v_3: t_2, 1, a[0] = 0, a[1] = 1$

threadIdx.x=0

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MPOR Applied to CUDA-based Programs

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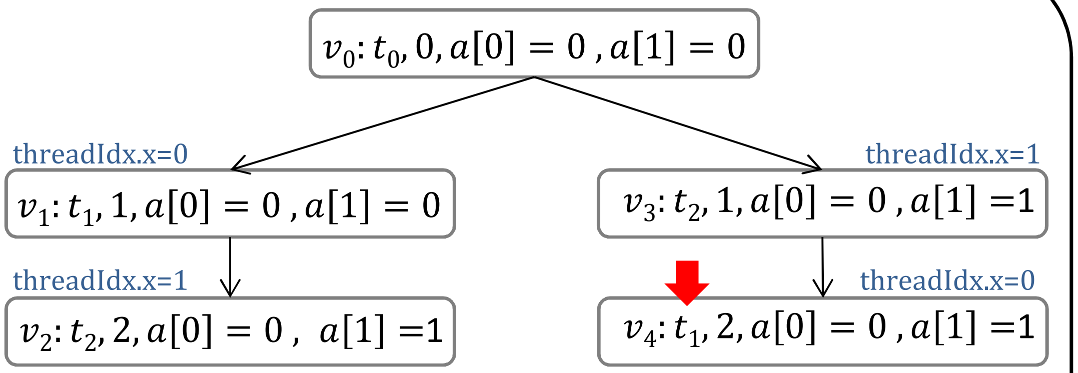

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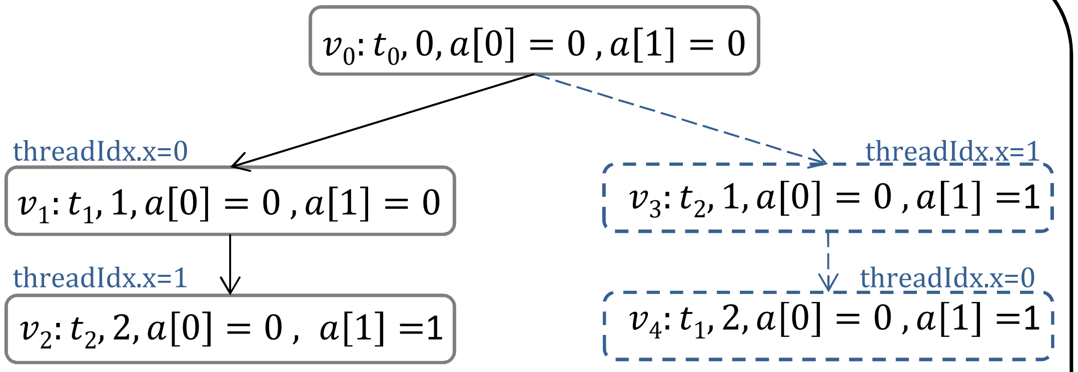

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threadIdx.x=1
$v_3: t_2, 1, a[0] = 0, a[1] = 1$

threadIdx.x=0
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$t_1 \rightarrow t_2$ or $t_2 \rightarrow t_1$ result in the same state, this is an independent transition

MPOR Applied to CUDA-based Programs

- MPOR algorithm in the ESBMC-GPU

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```
kernel (int *a)
   if(a[1]==1)
      a[threadIdx.x+2] = threadIdx.x ;
   else
      a[threadIdx.x] = threadIdx.x;
```

$v_0: t_0, 0, a[0] = 0\ , a[1] = 0$

MPOR Applied to CUDA-based Programs

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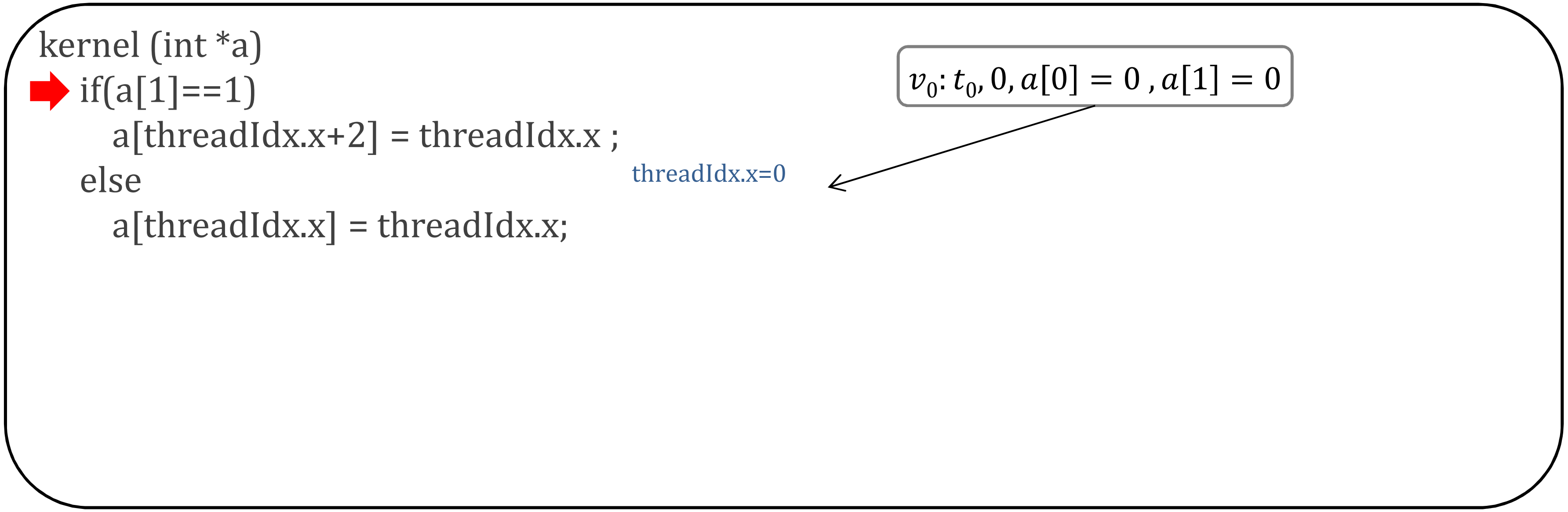

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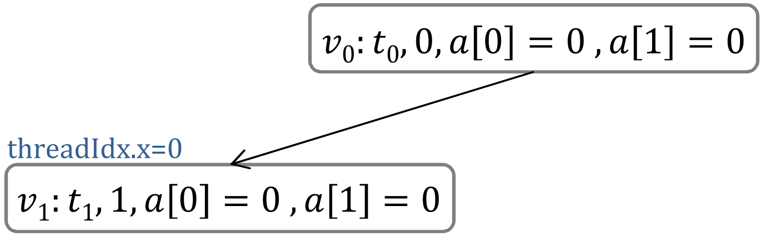
$v_0: t_0, 0, a[0] = 0 , a[1] = 0$

threadIdx.x=0

$v_1: t_1, 1, a[0] = 0 , a[1] = 0$

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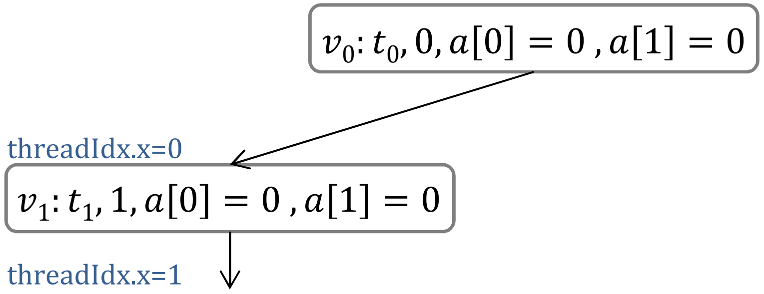

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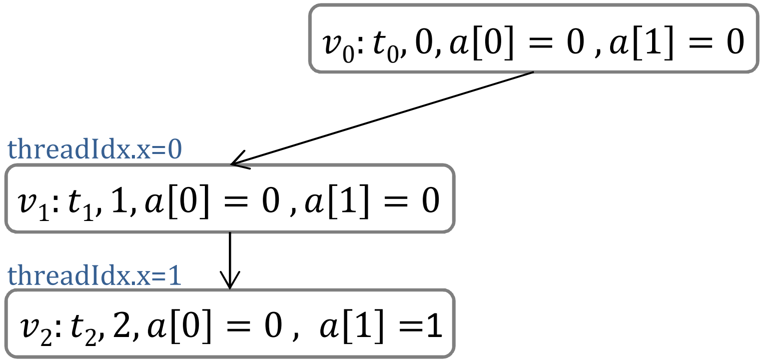

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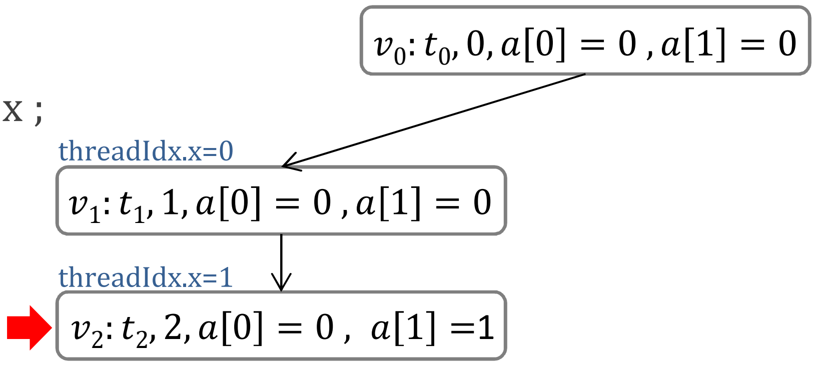

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➡ $v_2: t_2, 2, a[0] = 0, a[1] = 1$

$t_1 \rightarrow t_2$

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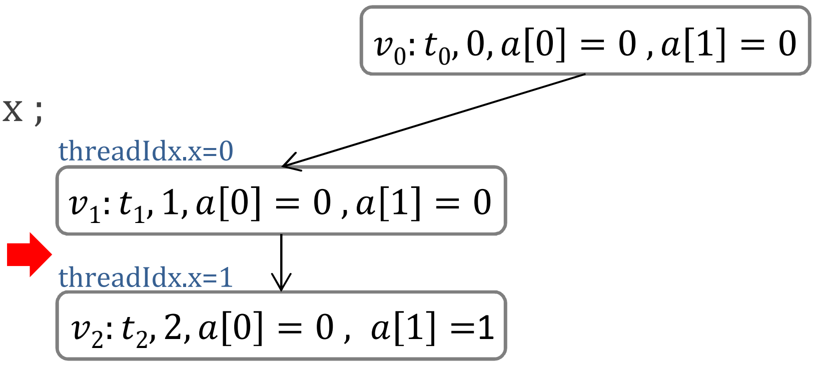

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threadIdx.x=0

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➡ threadIdx.x=1

$v_2: t_2, 2, a[0] = 0, a[1] = 1$

$t_1 \rightarrow t_2$

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$t_1 \rightarrow t_2$

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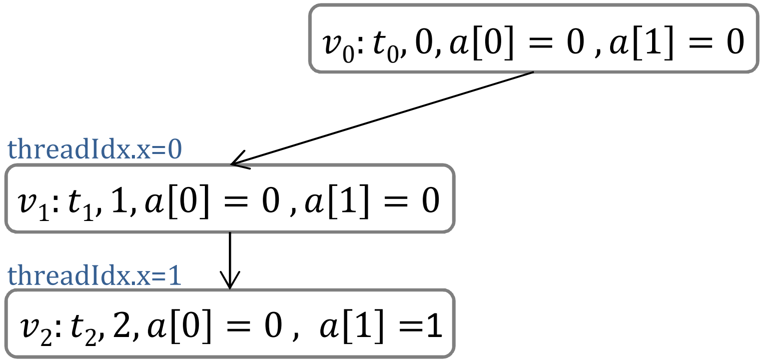

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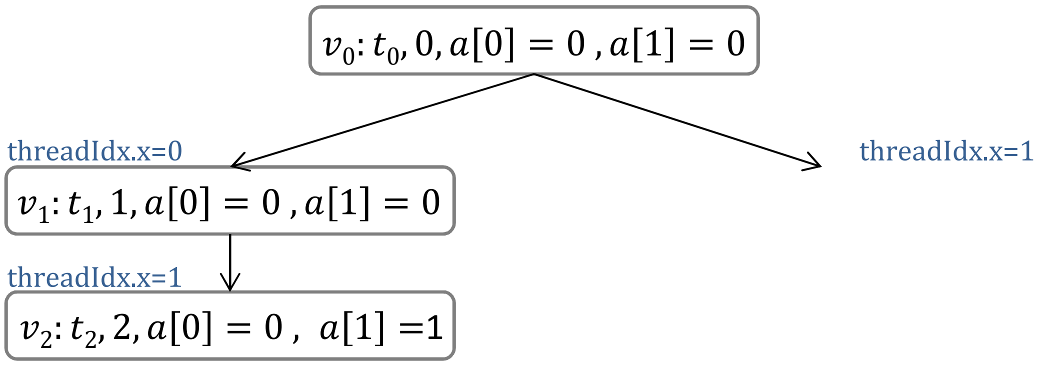

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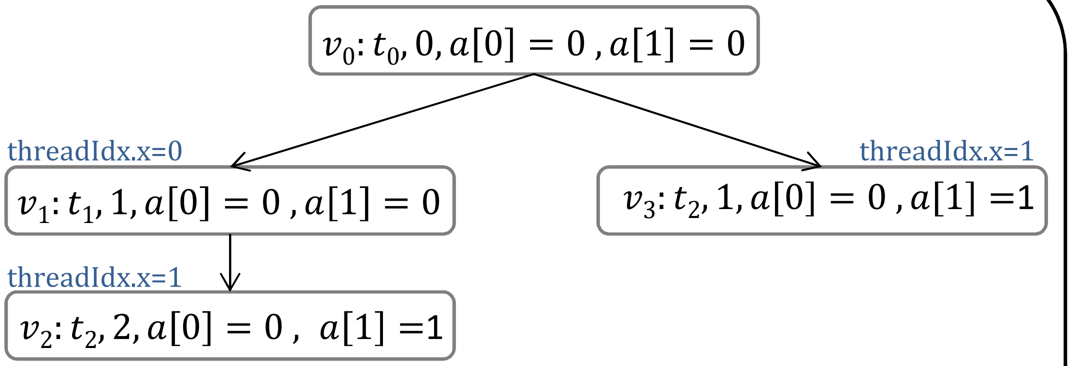

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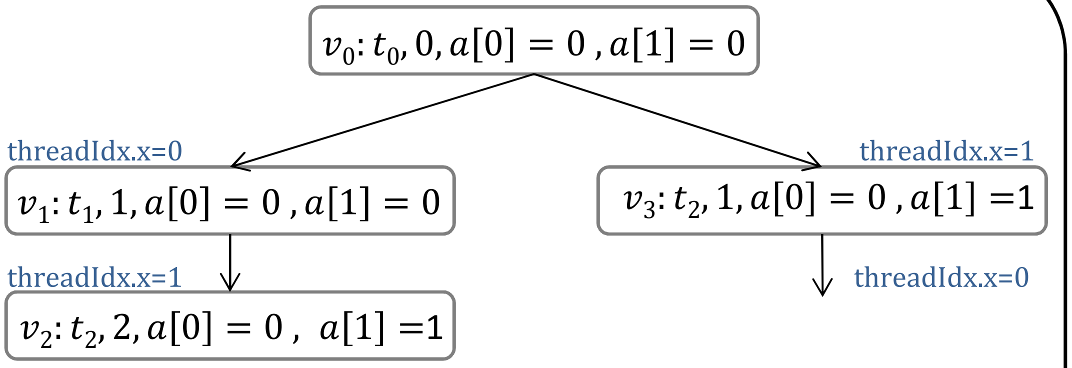

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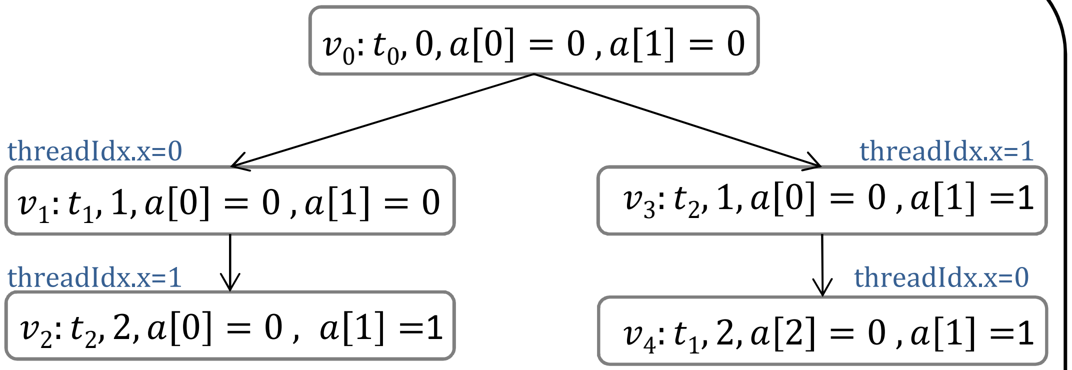

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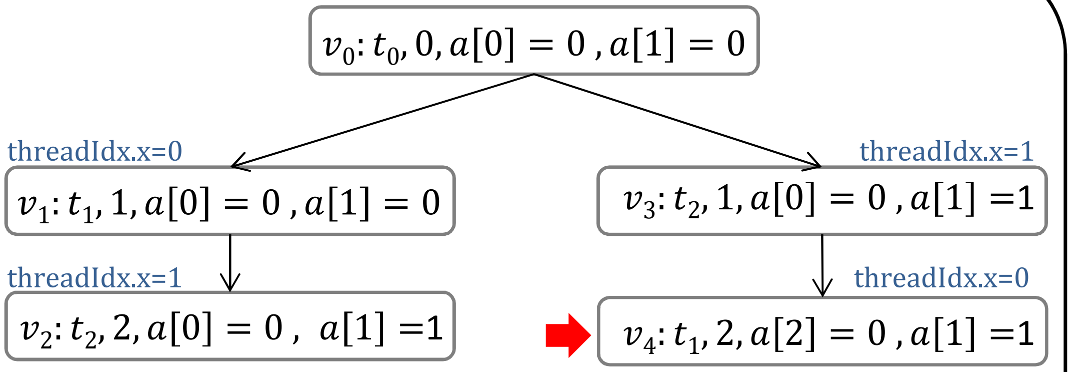

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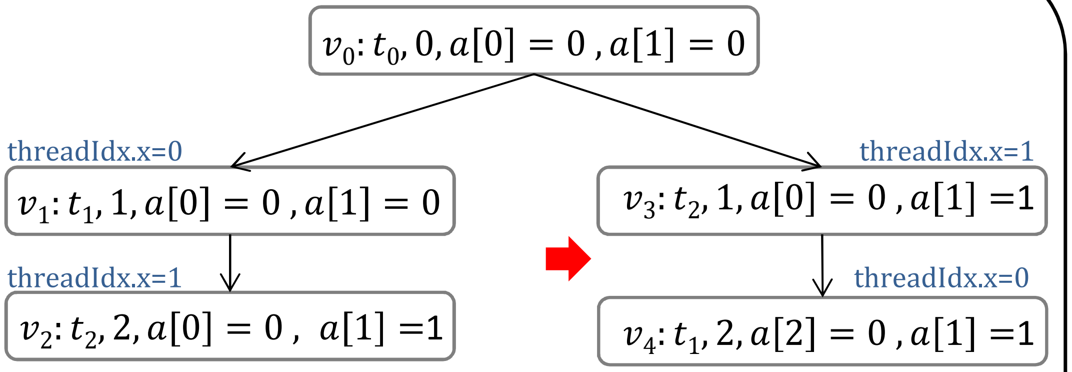
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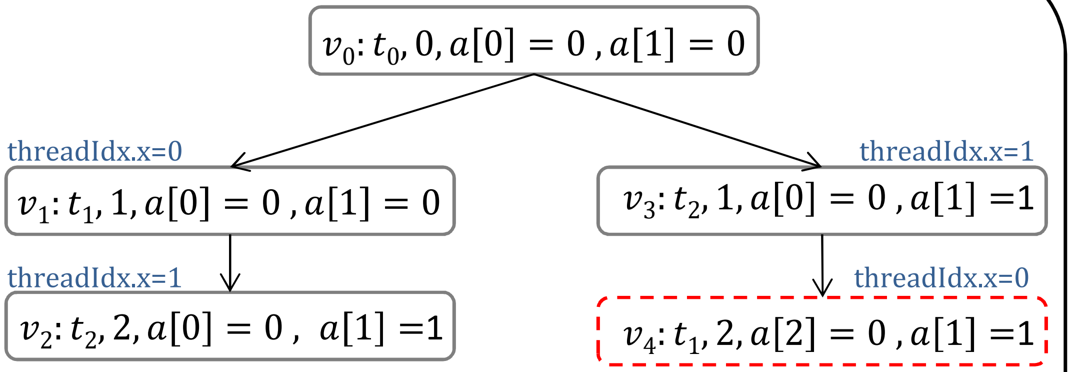

$t_1 \rightarrow t_2$ computes a different state of $t_2 \rightarrow t_1$, resulting in dependent transitions

Two-threads Analysis

- Reduction for two-threads during the program verification

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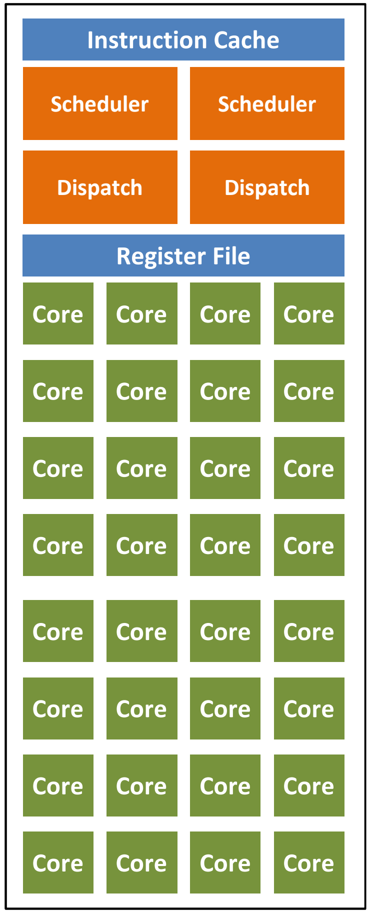
    - This proposition holds due to the GPU architecture
  - This technique is also used by other GPU kernel verification tools (*e.g.,* GPUVerify and PUG)

Two-threads Analysis in Fermi

Fermi - Stream Multiprocessor



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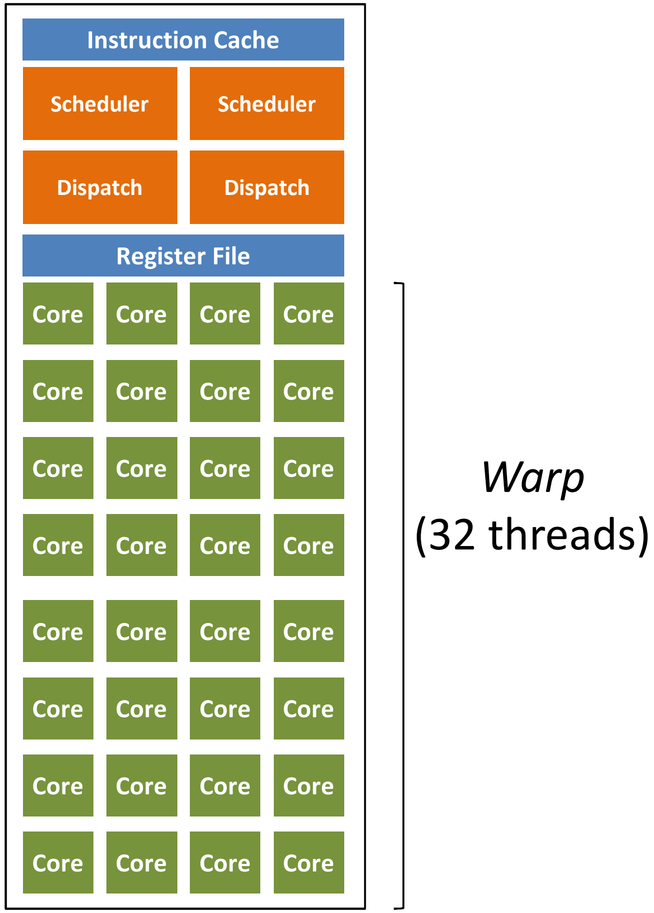

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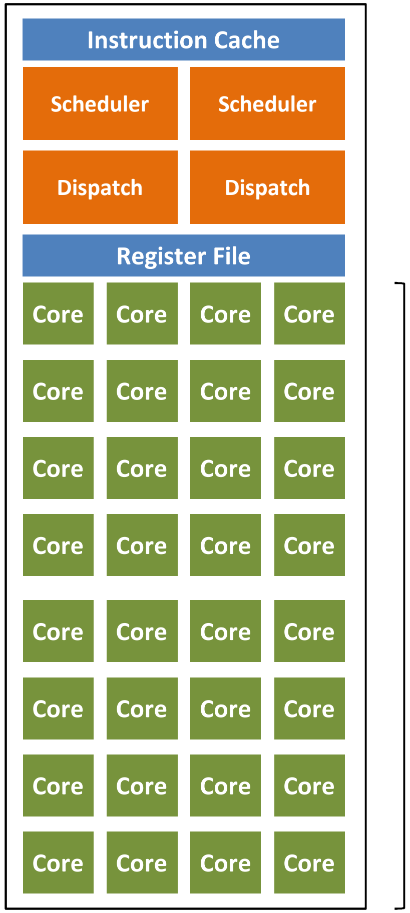
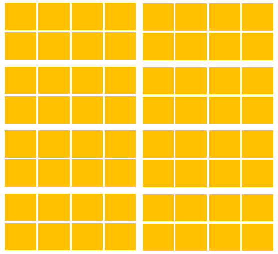


Warp
(32 threads)

Block of threads
(64 threads)



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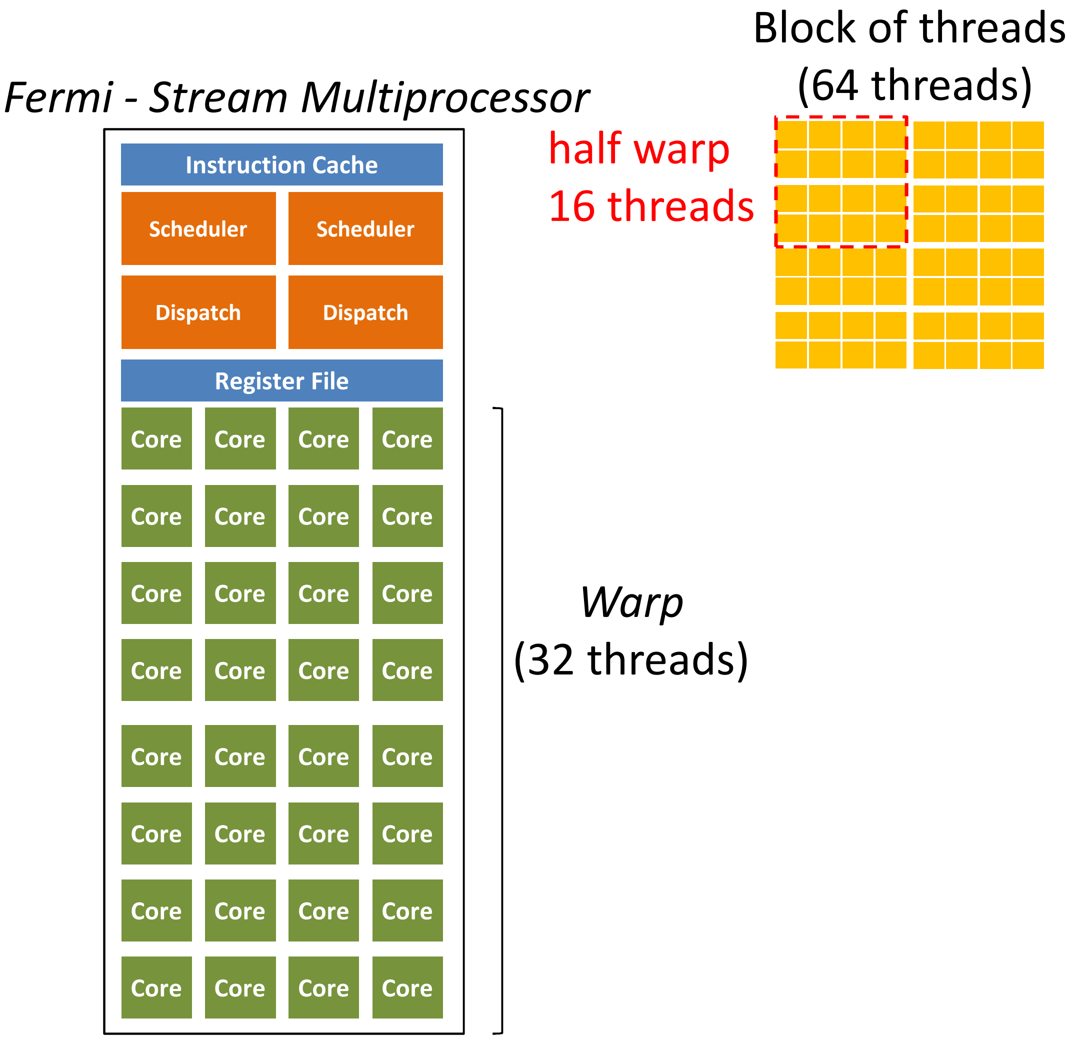

Fermi - Stream Multiprocessor

Instruction Cache

Scheduler Scheduler

Dispatch Dispatch

Register File

Core Core Core Core
Core Core Core Core
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Warp
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half warp
16 threads

One thread group is processed by a half warp in the SM

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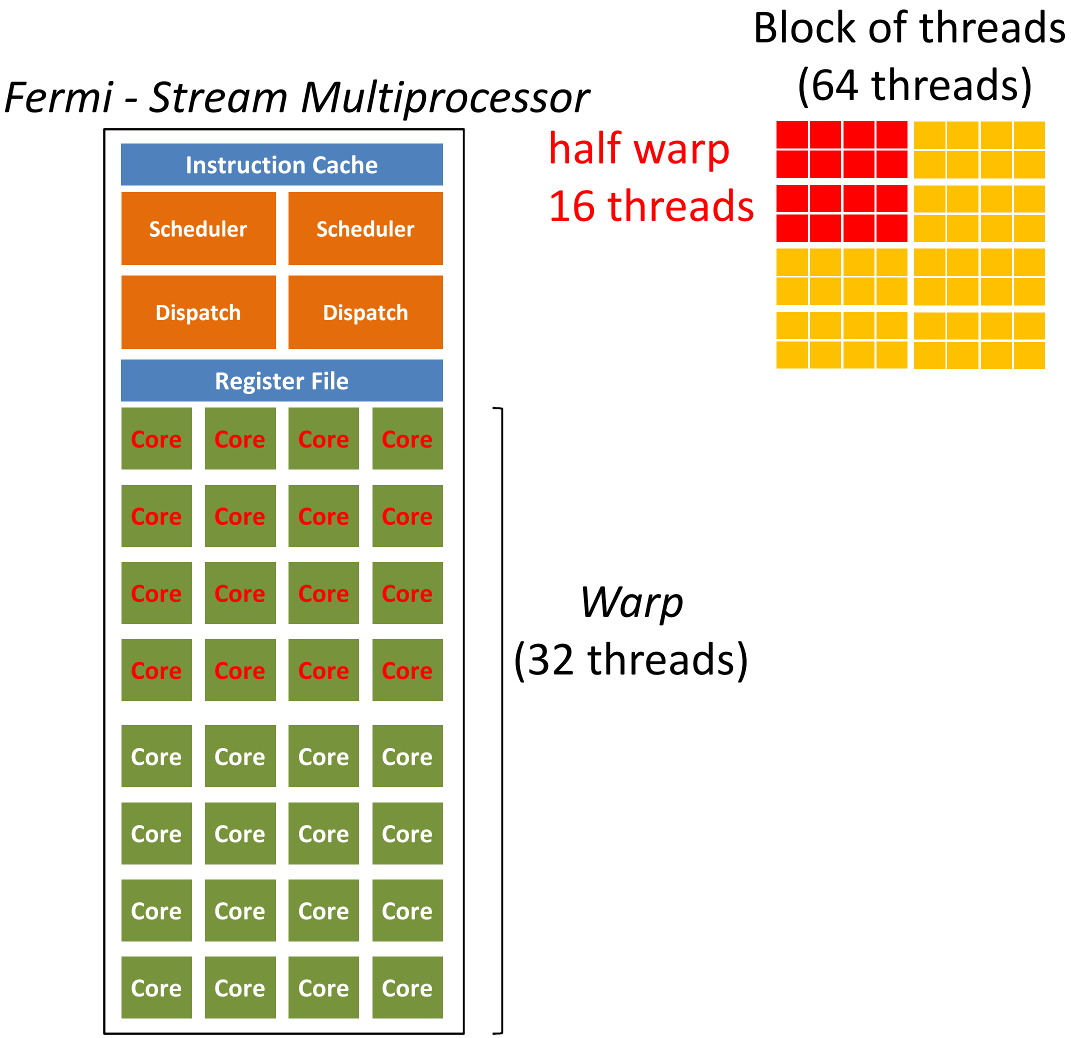

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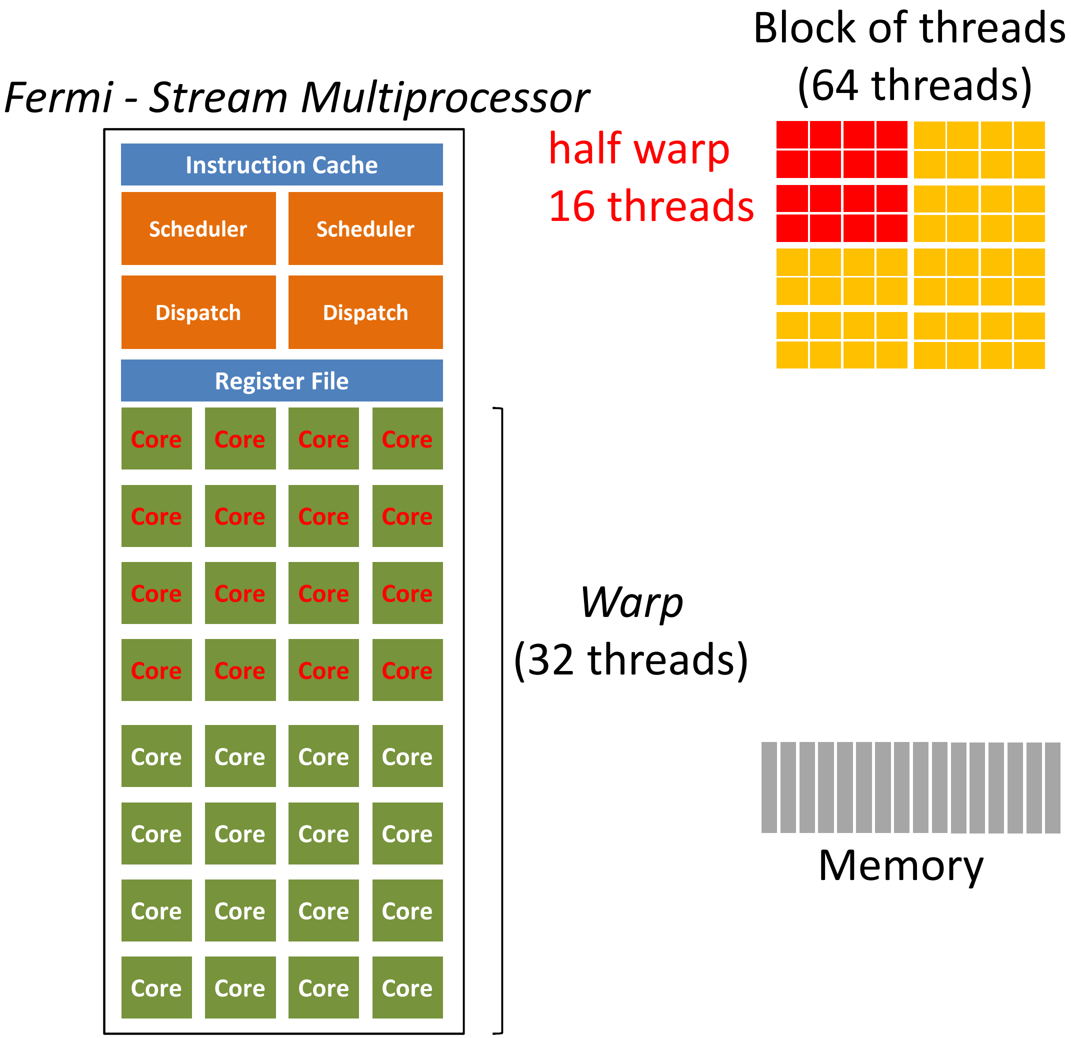

Fermi - Stream Multiprocessor

Block of threads
(64 threads)

half warp
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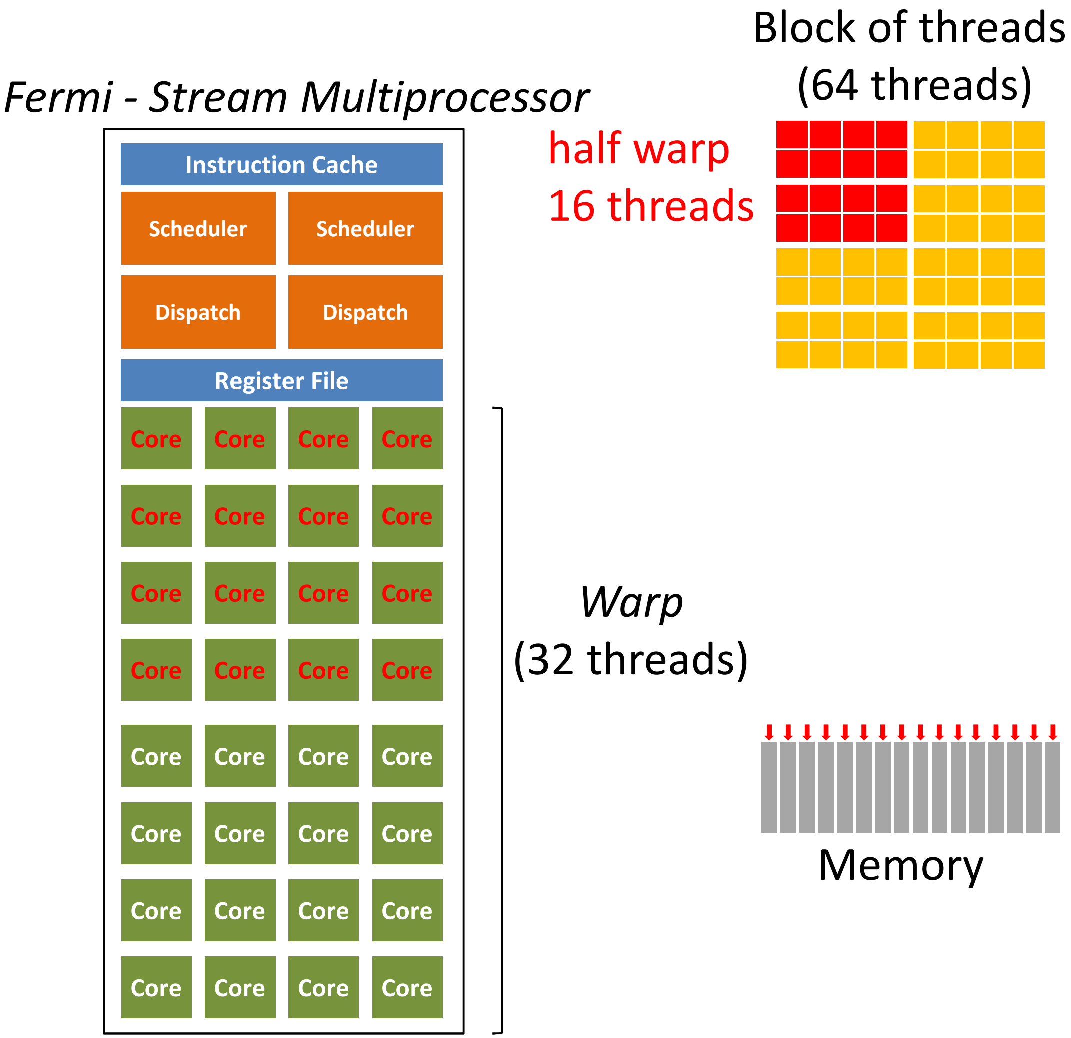
Warp
(32 threads)

Memory

Two-threads Analysis in Fermi



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Memory

there is no data race to access different memory positions

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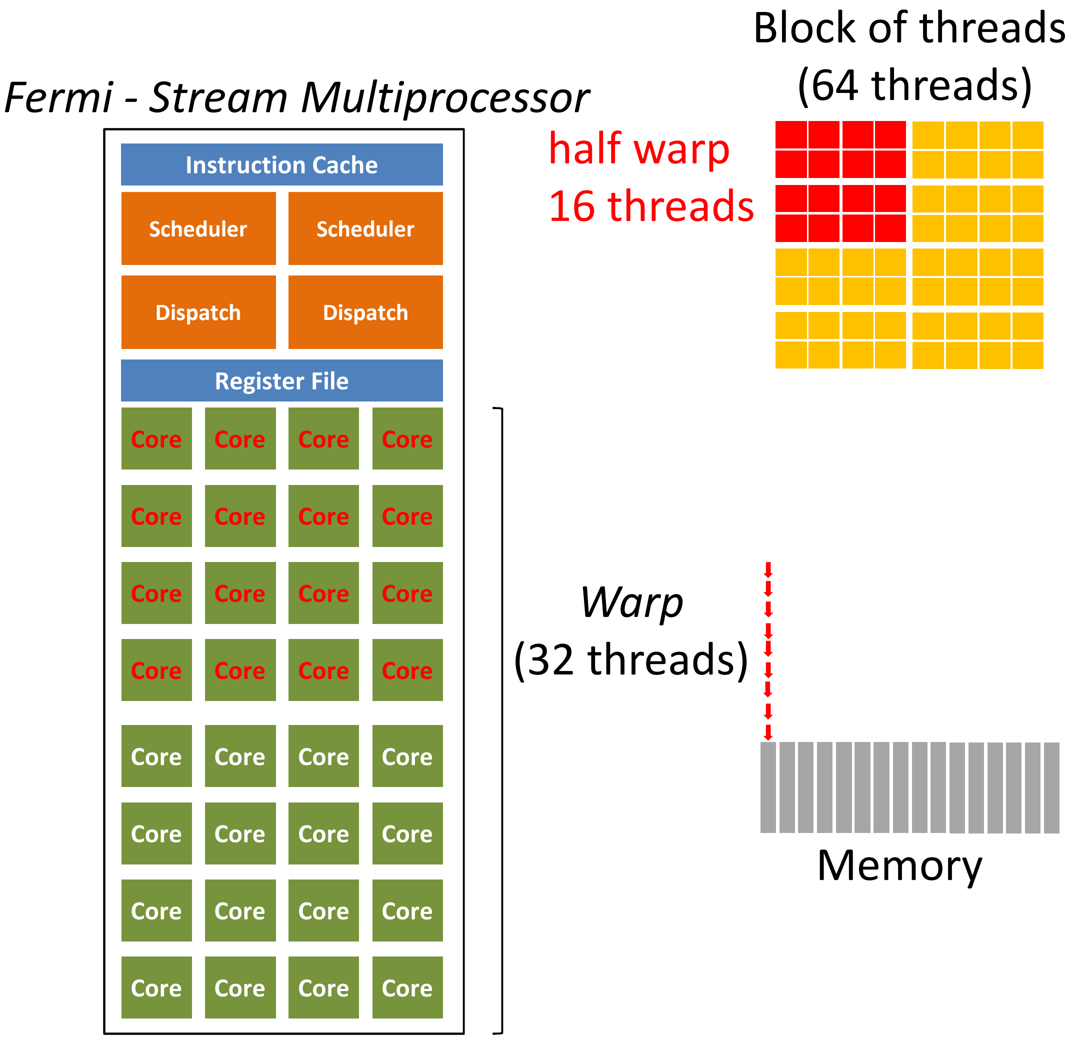

access to the same memory position leads to data race

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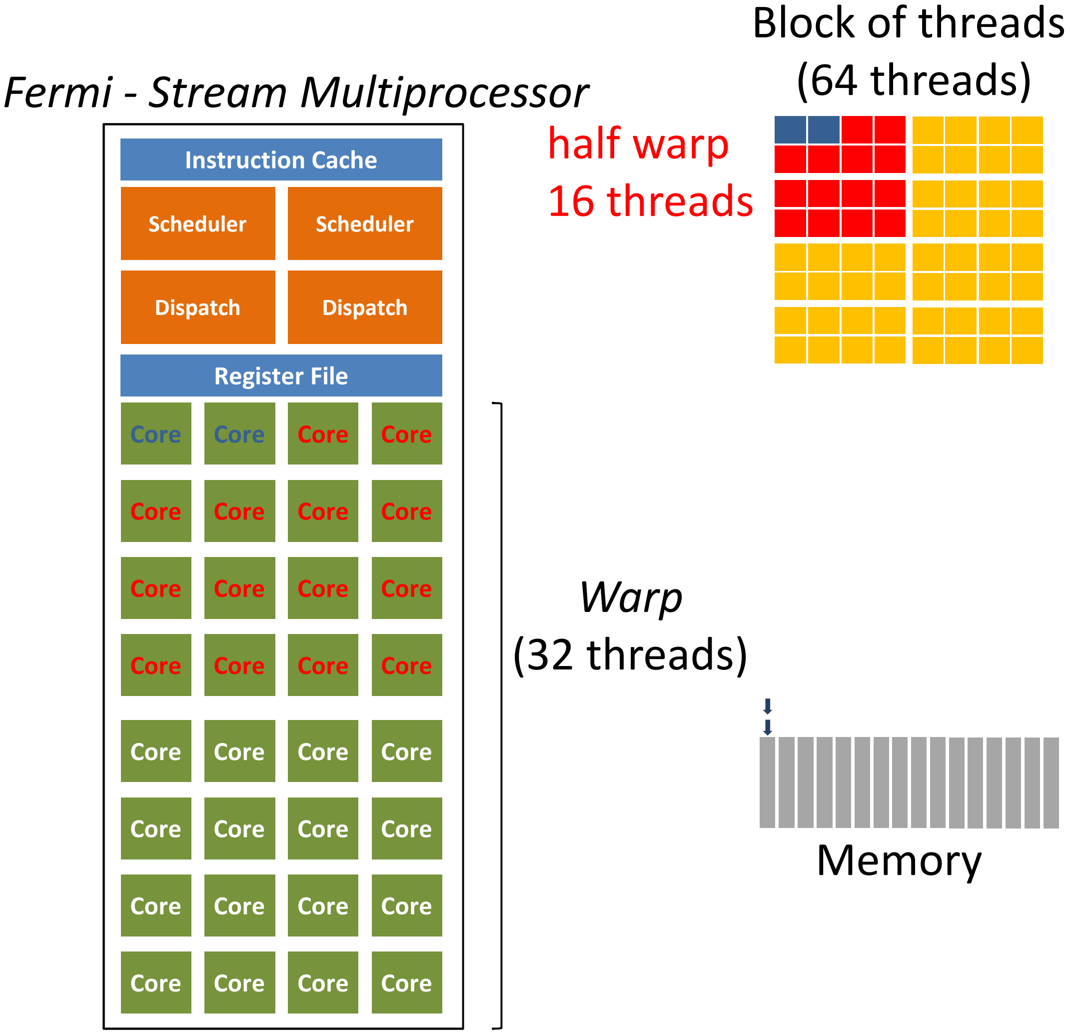

If the error is detected in a half warp threads, it also shows up for two-threads

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- **Objective:** check whether ESBMC-GPU is able to correctly verify CUDA-based programs

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  - symbolic execution, POR, and GPU threads with Pthread

Experimental Results

Result\Tool	**ESBMC-GPU**	**GKLEE**	**GPUVERIFY**	**PUG**	**CIVL**
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False Correct	**67**	56	30	15	24
True Incorrect	1	14	9	7	**0**
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Total number of benchmarks in which the program does not contain errors

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ESBMC-GPU achieves the highest "True Correct" results

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ESBMC-GPU detects data race, array out of bounds, null pointer, and user-specified assertion

Experimental Results

Result\Tool	**ESBMC-GPU**	**GKLEE**	**GPUVERIFY**	**PUG**	**CIVL**
True Correct	**60**	53	58	39	23
False Correct	**67**	56	30	15	24
True Incorrect	1	14	9	7	**0**
F			8	11	**3**
N			49	82	104
Time(s)	811	128	147	**12**	158

Total number of benchmarks in which the program had an error but the verifier did not find it

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Result\Tool	**ESBMC-GPU**	**GKLEE**	**GPUVERIFY**	**PUG**	**CIVL**
True Correct	**60**	53	58	39	23
False Correct	**67**	56	30	15	24
True Incorrect	1	14	9	7	**0**
False Incorrect	**3**	7	[illegible]	[illegible]	**3**
Not supported	**23**	24	49	82	104
Time(s)	811	128	147	**12**	158

CIVL did not present any “True Incorrect” result

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Result\Tool	**ESBMC-GPU**	**GKLEE**	**GPUVERIFY**	**PUG**	**CIVL**
True Correct	**60**	53	58	39	23
[illegible]	[illegible]	56	30	15	24
[illegible]	[illegible]	14	9	7	**0**
False Incorrect	**3**	7	8	11	**3**
Not supported	**23**	24	49	82	104
Time(s)	811	128	147	**12**	158

Total number of benchmarks in which an error is reported for a program that fulfills the specification

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ESBMC-GPU and CIVL present the lowest "False Incorrect" results

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Time(s)	811	128	147	**12**	158

Total number of benchmarks which are not supported by the tool

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ESBMC-GPU supports the largest number of benchmarks

Experimental Results

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Not supported	**23**	24	[illegible]	[illegible]	[illegible]
Time(s)	811	128	147	**12**	158

PUG is the fastest verifier, but it does not present the highest covegare

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- Future work
  - Barrier divergence detection
  - Support to new memory types (*e.g.,* pinned and unified)
  - Techniques to reduce interleavings (lazy sequentialization)