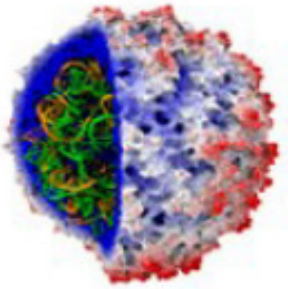
31st ACM/SIGAPP Symposium on Applied Computing

SMT-Based Context-Bounded Model Checking for CUDA Programs

Phillipe Pereira, Higo Albuquerque, Hendrio Marques, 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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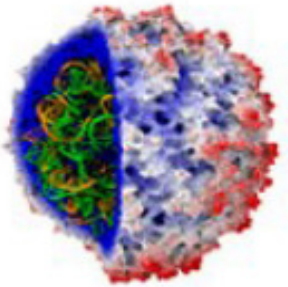

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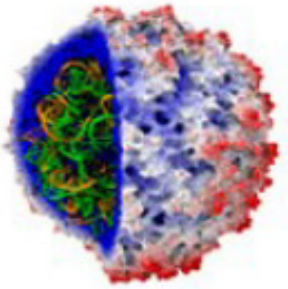

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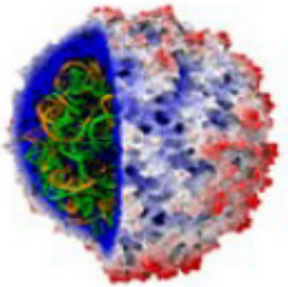

- We need to ensure **code correctness** in safety-critical GPU applications

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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)
- Compare **ESBMC-GPU** experimental results with other **state-of-art software verifiers** for CUDA

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- COM aims to
  - **Abstractly** represent the associated CUDA libraries
    - checks **pre-** and **post-conditions**
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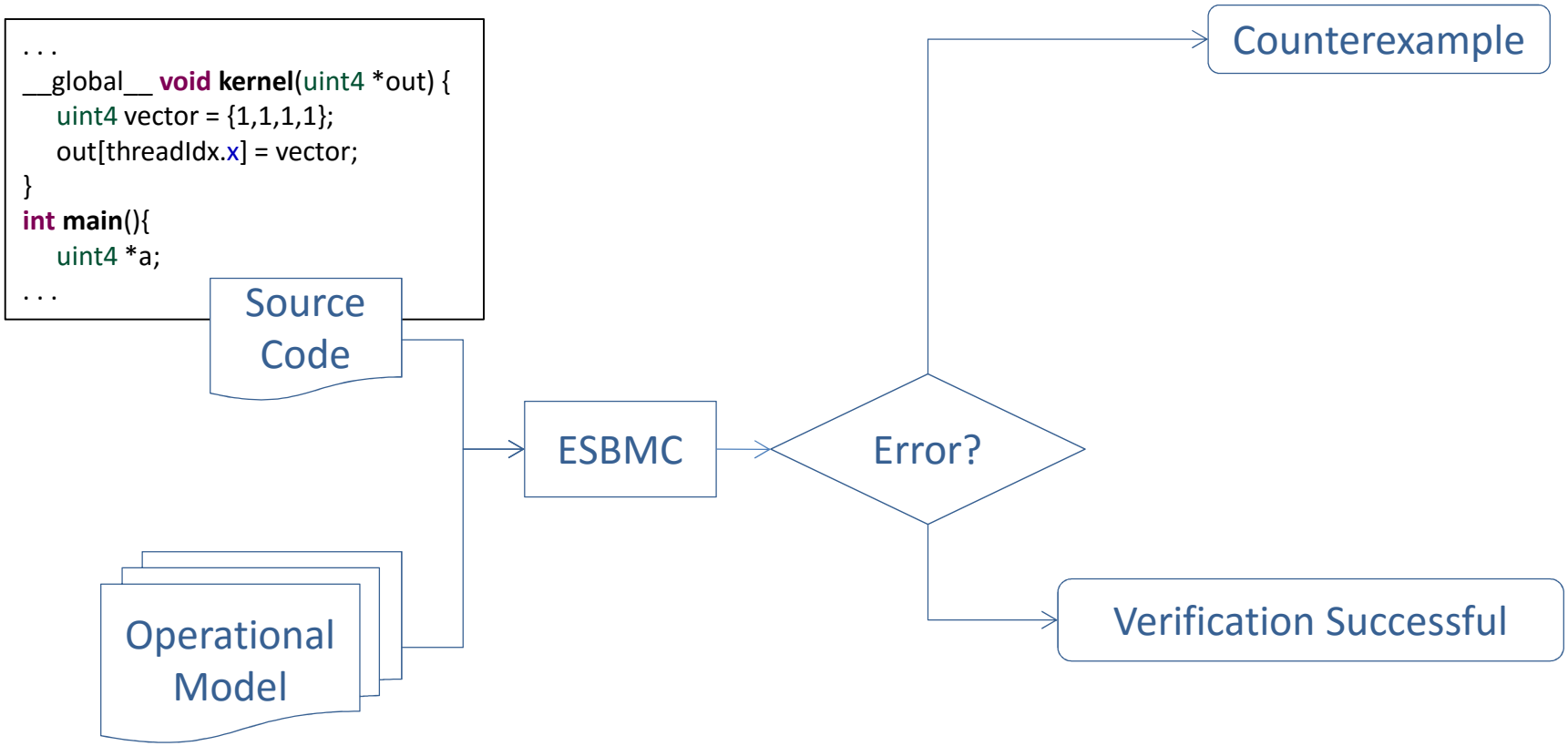
    - ESBMC++ (ECBS'13) and ESBMC^{QtOM} (SPIN'16)
- CUDA is a **proprietary platform**
  - CUDA Programming Guide and IDE Nsight

ESBMC-GPU: Verification Flow



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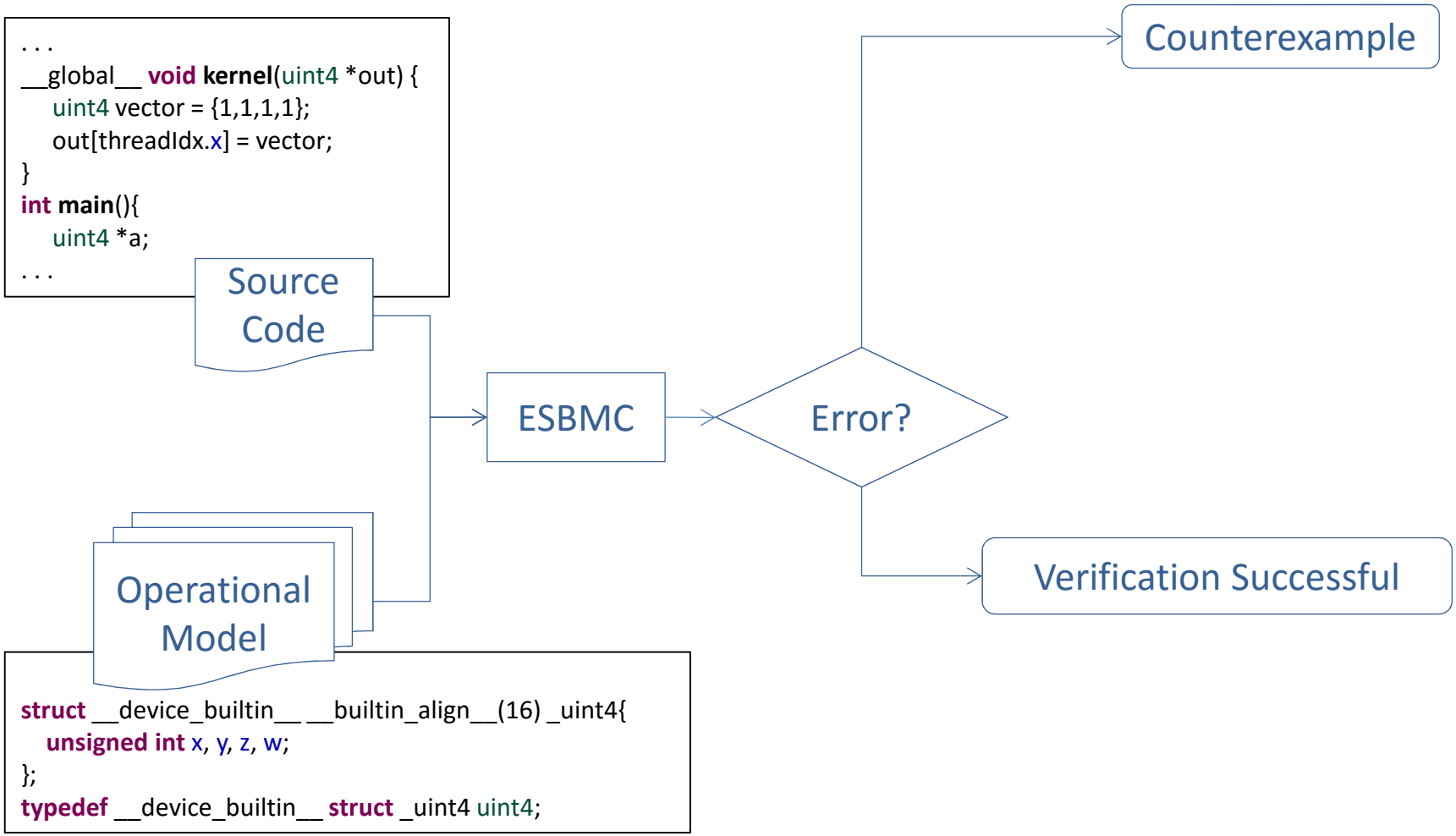

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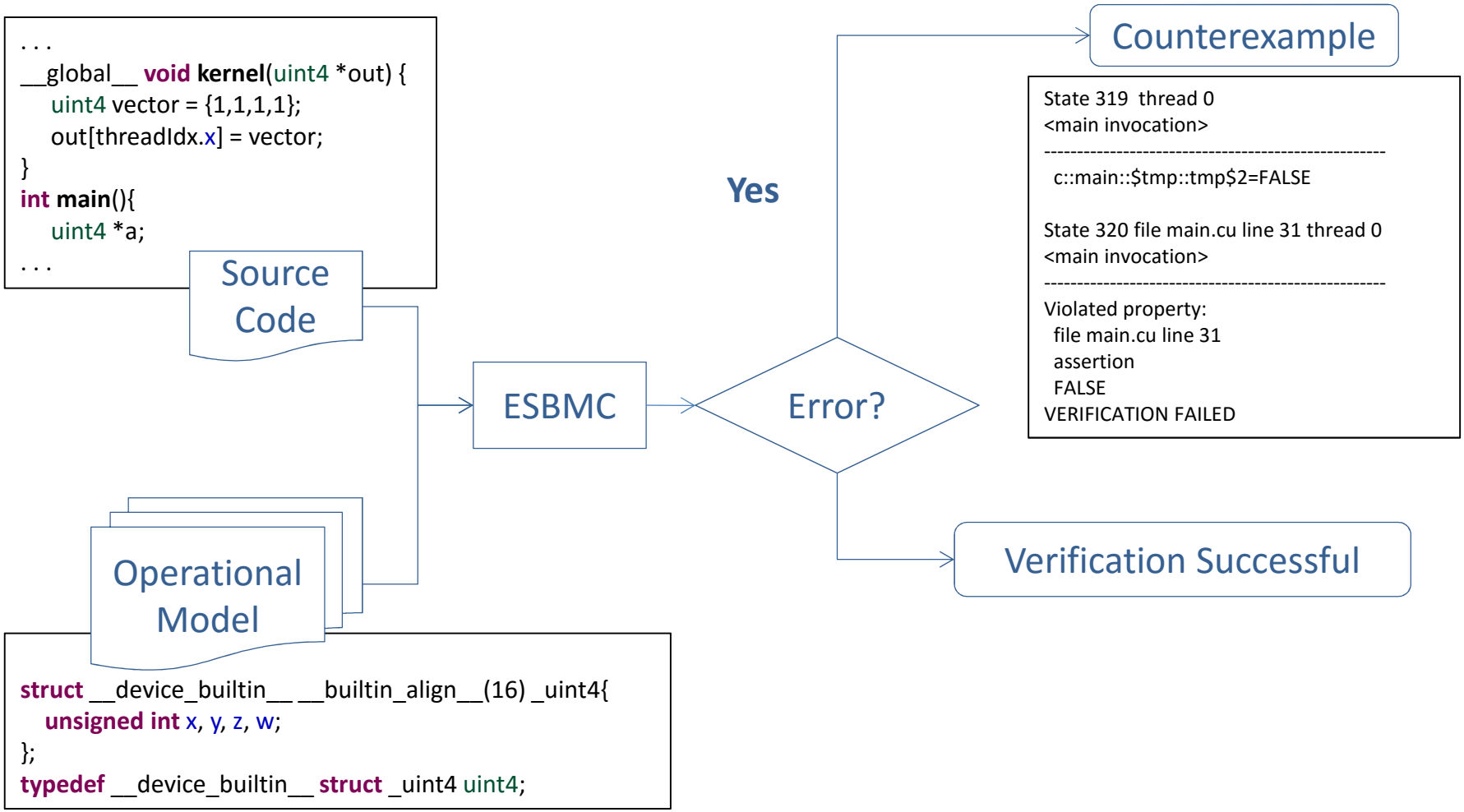

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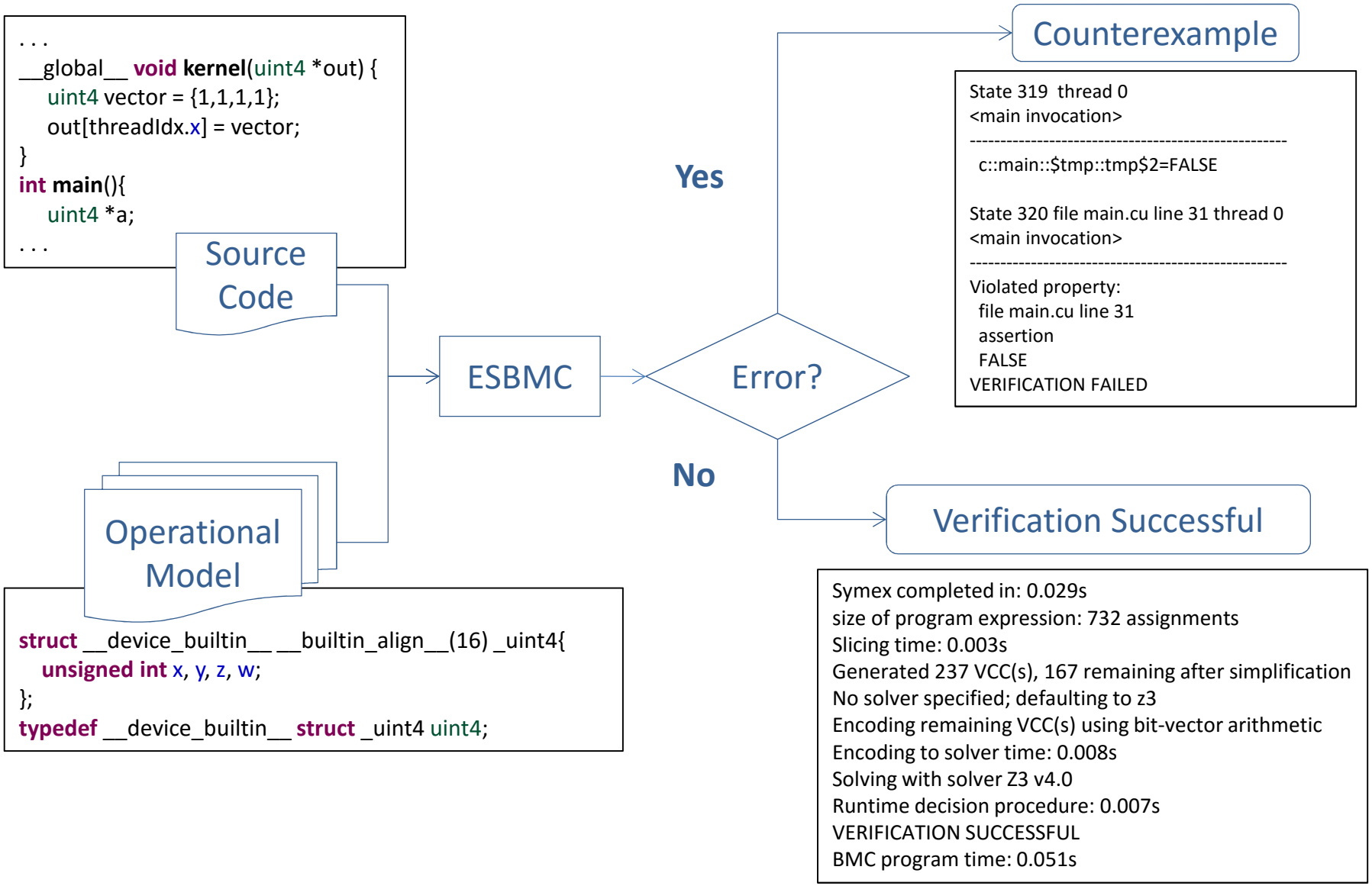

COM Implementation: *cudaMalloc*

```
#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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# 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;
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}
```

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

```
_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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  cudaMemcpy(a,dev_a,dth);
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  cudaFree(dev_a);
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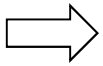

COM

Function conversion

cudaMalloc(&dev_a,size)

```
assert(size>0);
*dev_a=malloc(size);
if(*dev_a==NULL)
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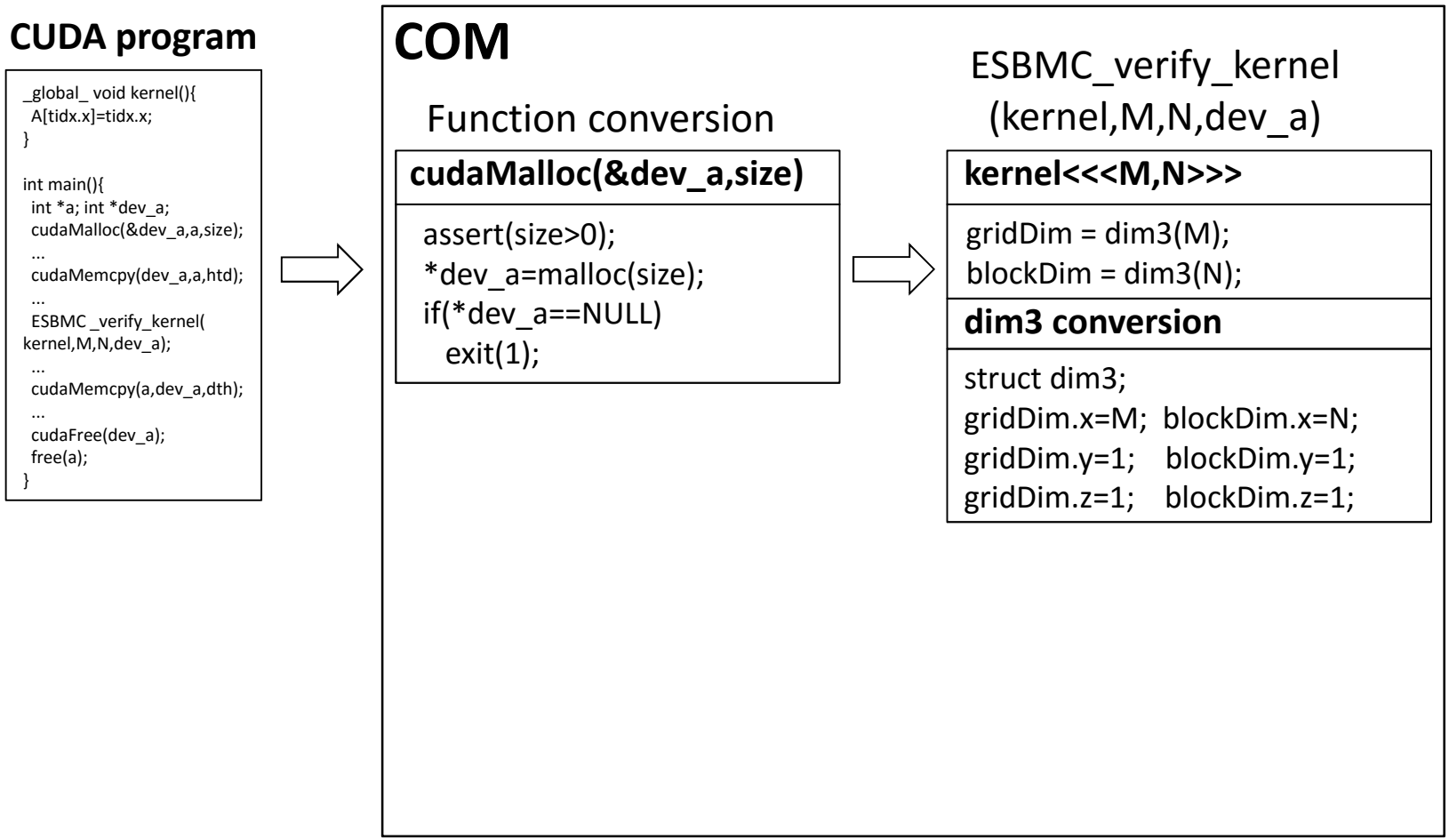

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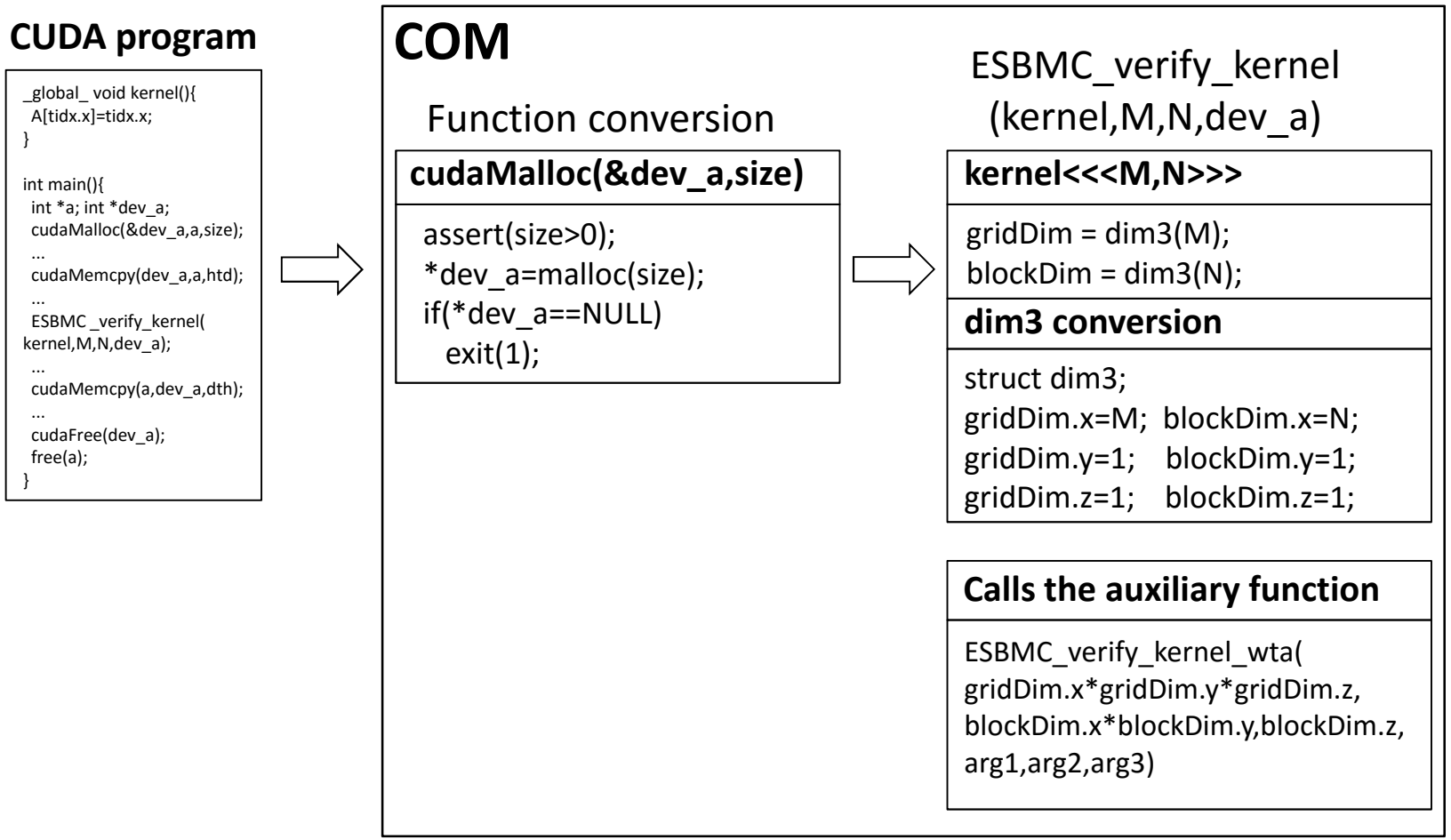

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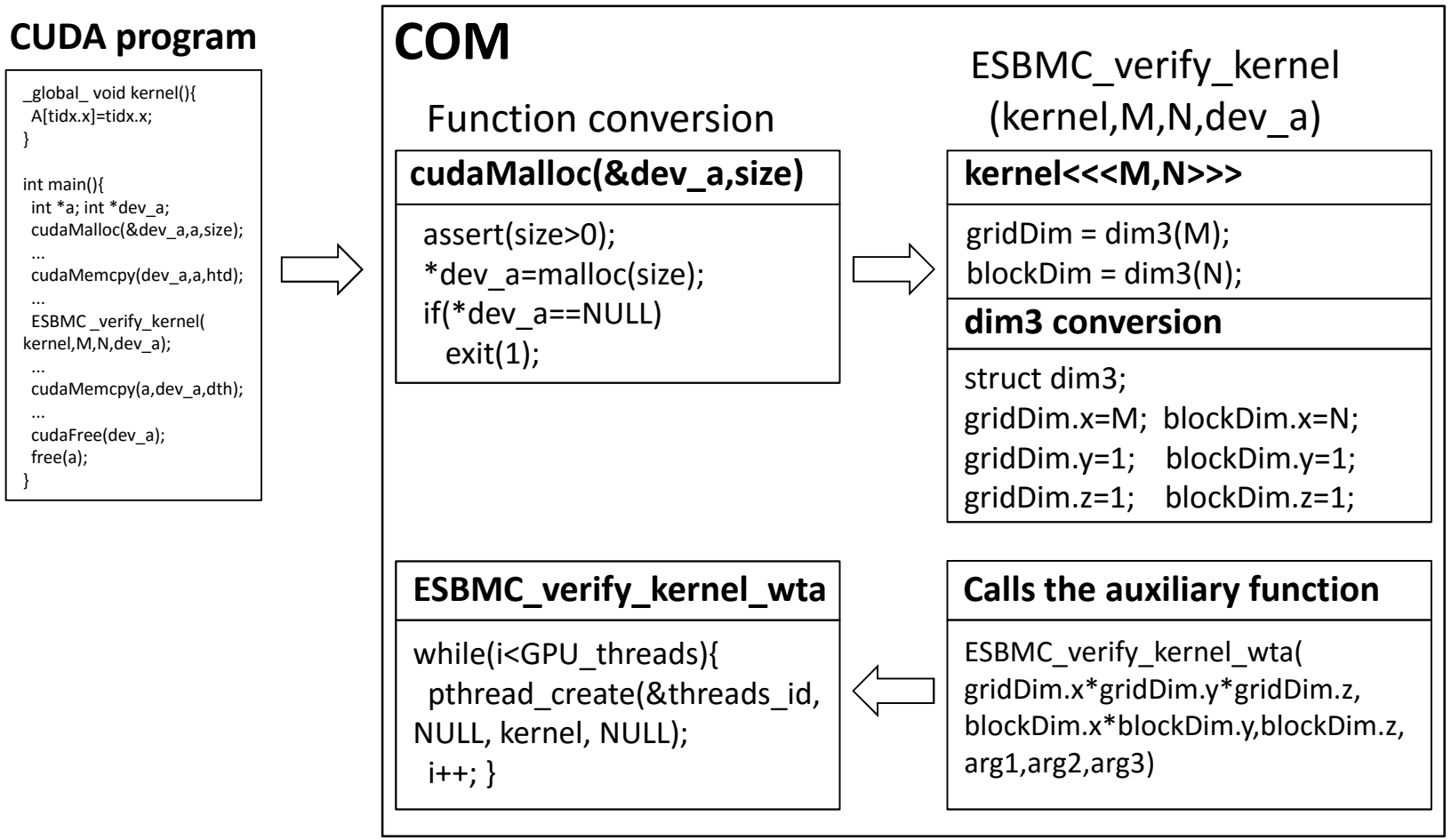

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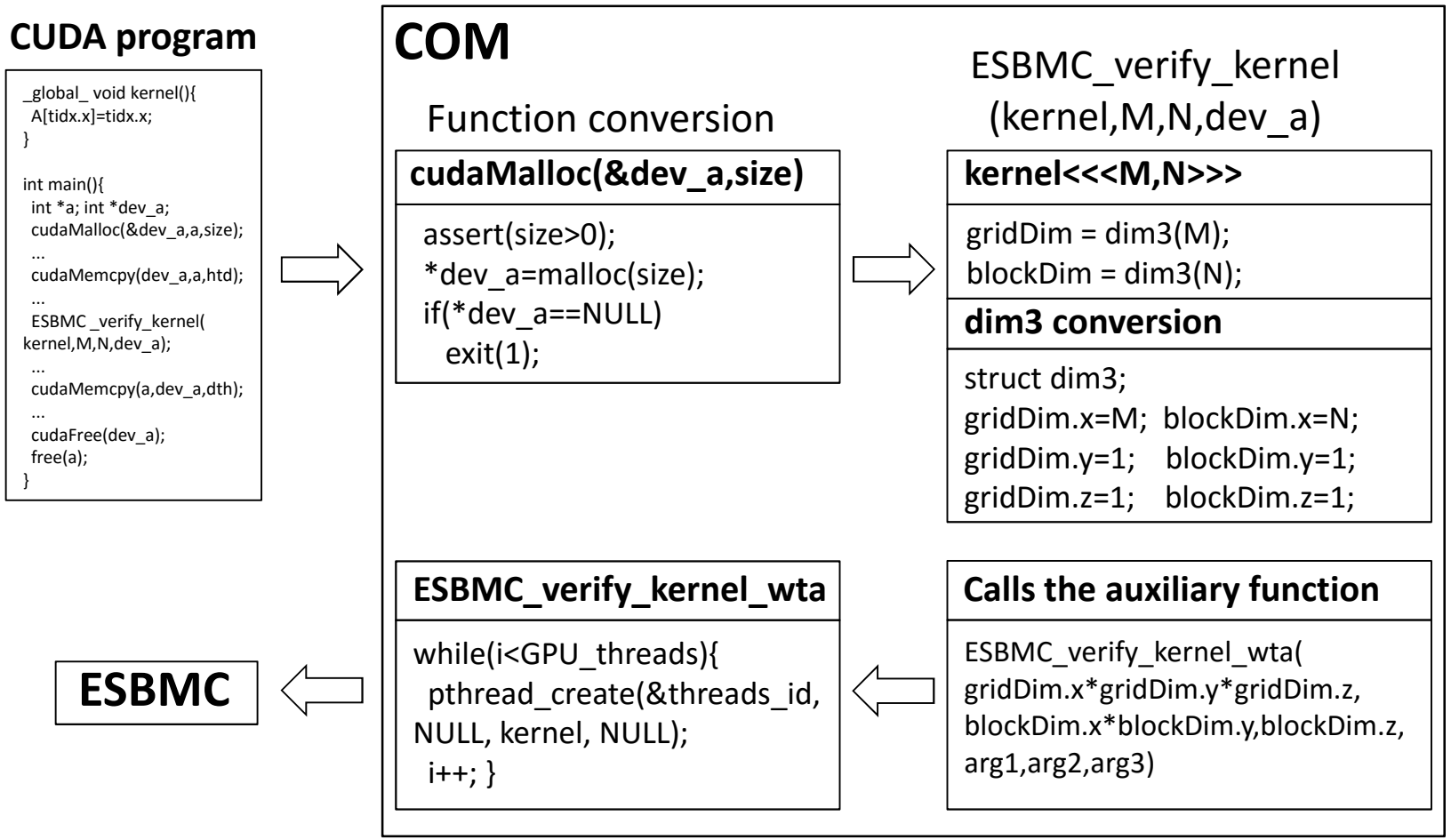

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- MPOR classifies thread transitions in a multi-threaded program
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- MPOR classifies thread transitions in a multi-threaded program
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- First application 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 (ν, 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
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5. Return “independent” on π and terminates
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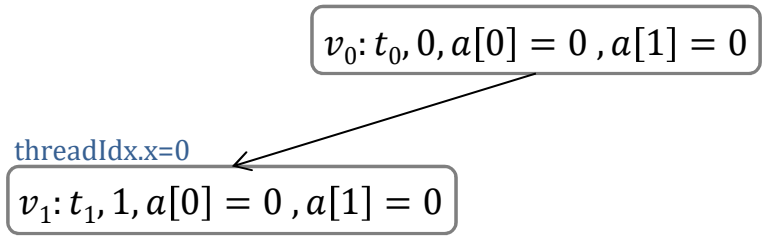

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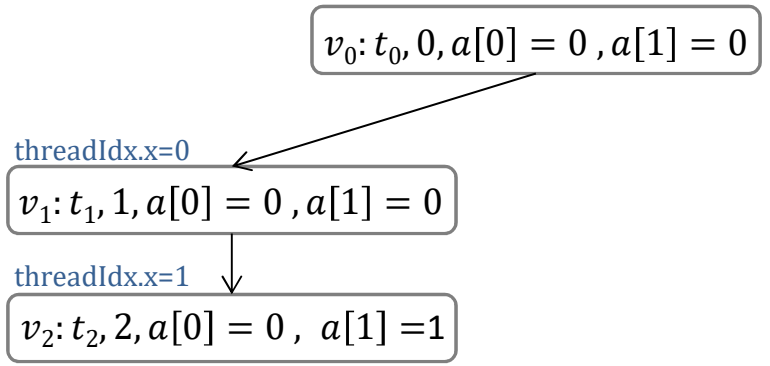

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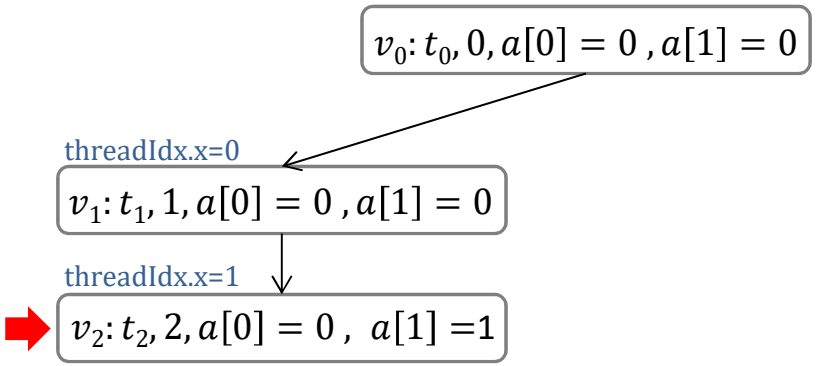

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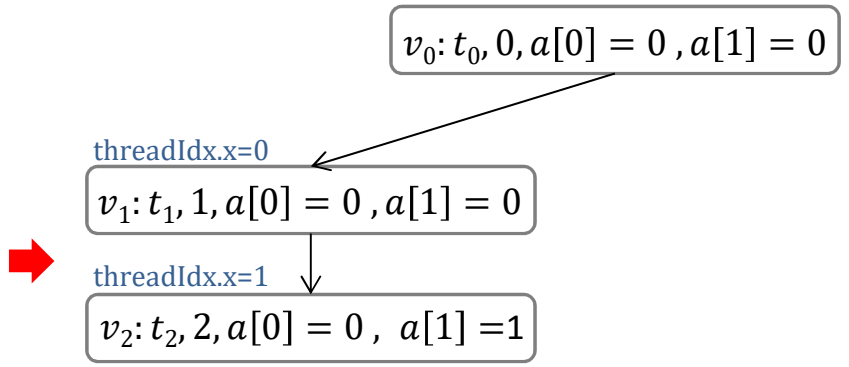

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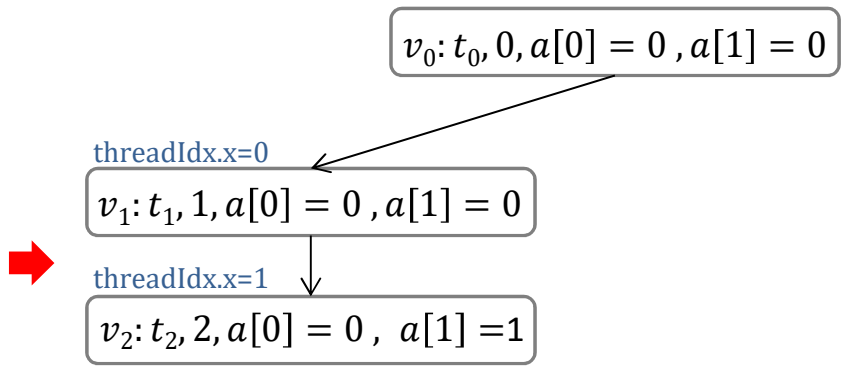

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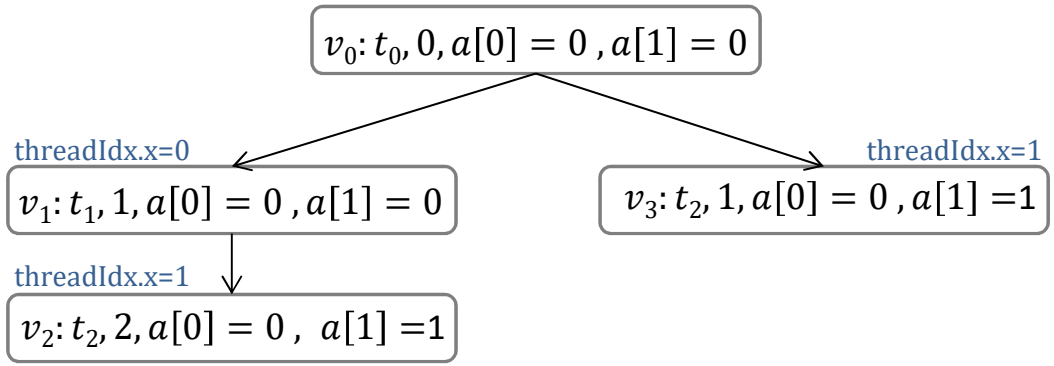

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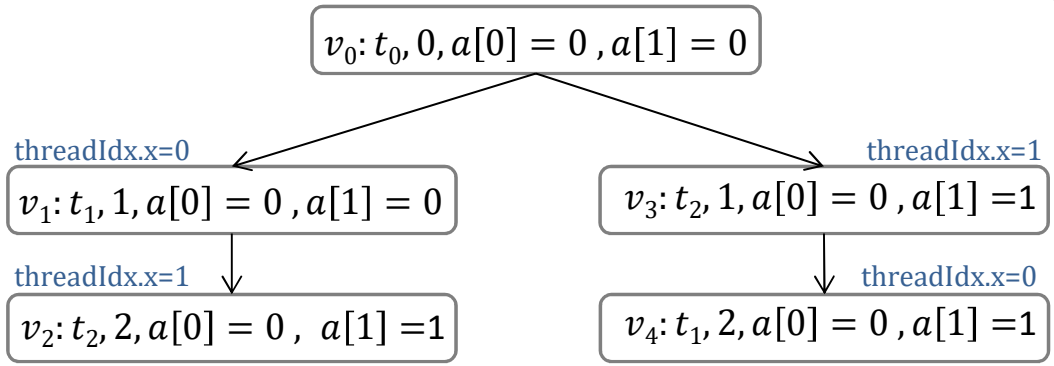

MPOR Applied to CUDA-based Programs

- MPOR algorithm in the ESBMC-GPU

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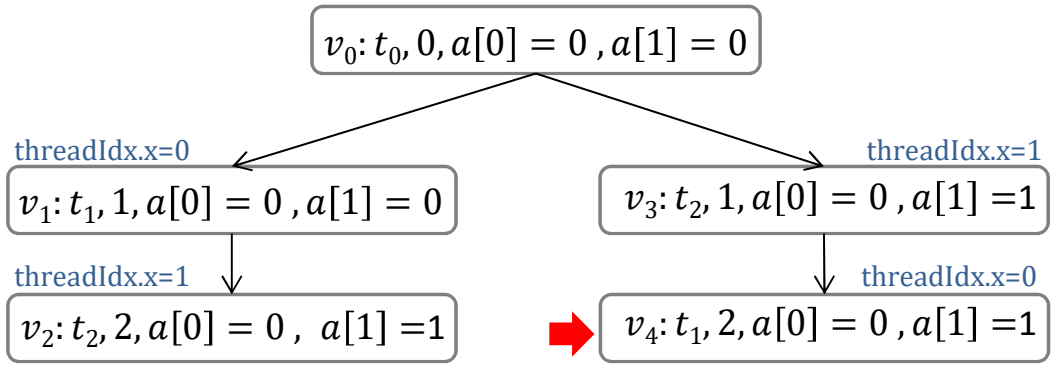

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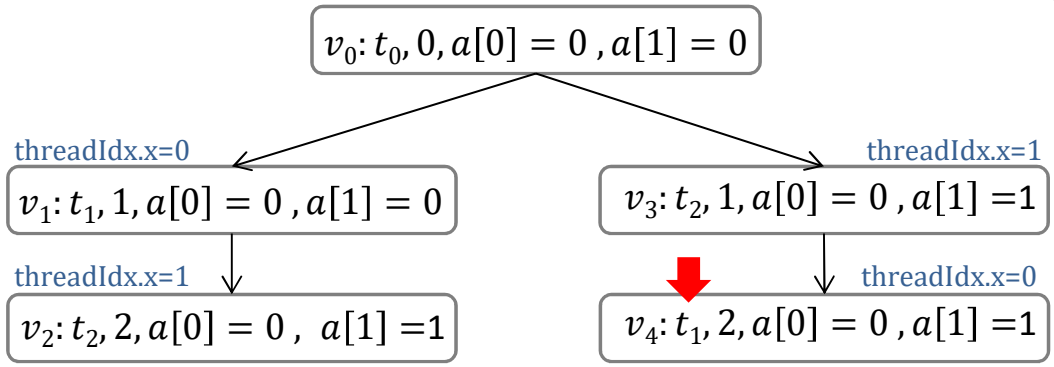

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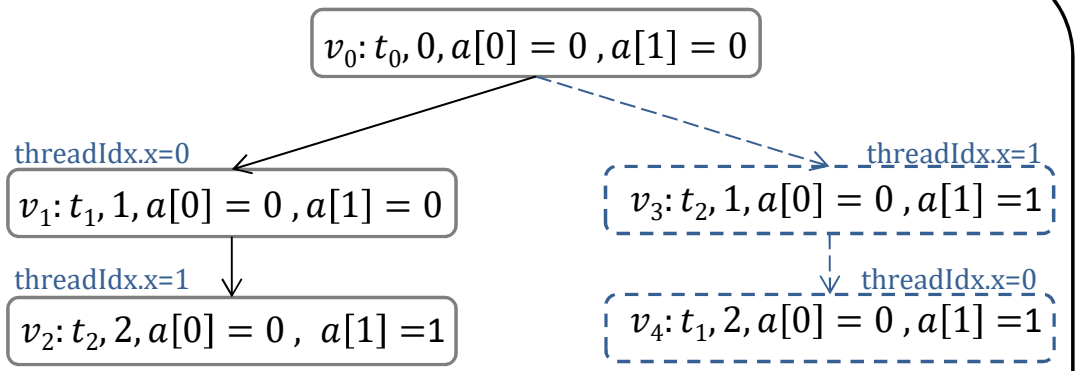

$t_1 \rightarrow t_2$ or $t_2 \rightarrow t_1$ result in the same state, this is an independent transition

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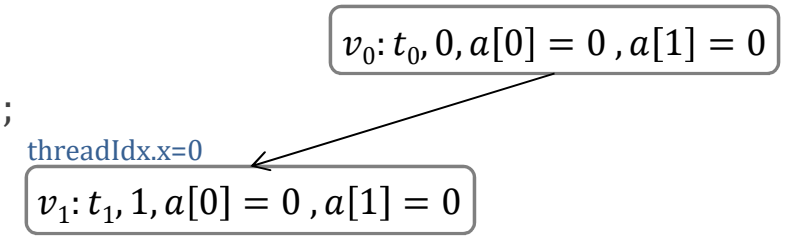

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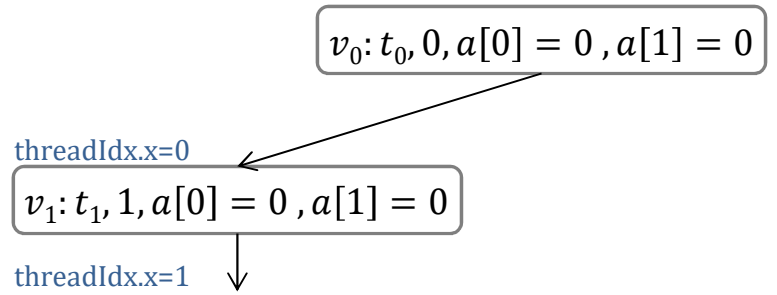

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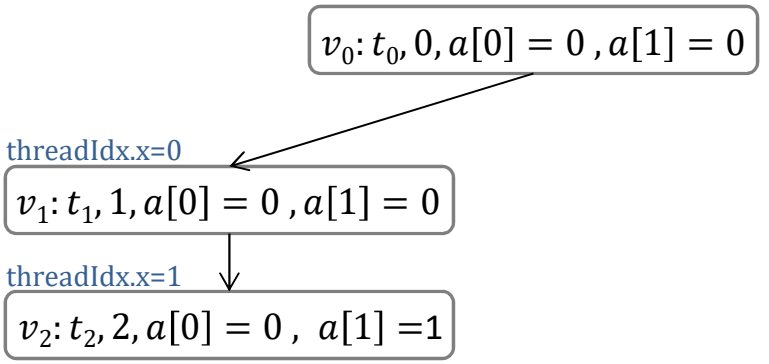

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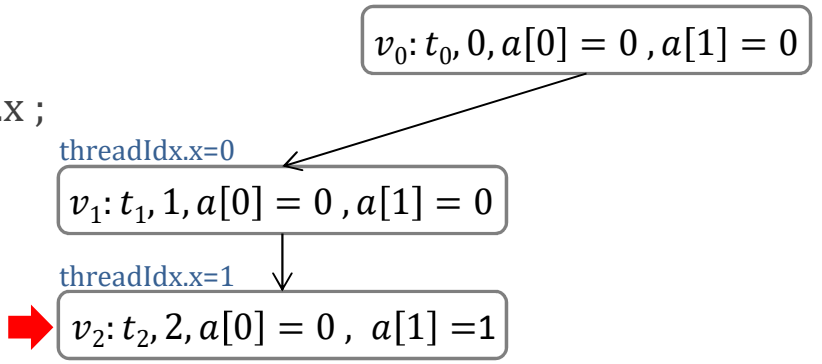

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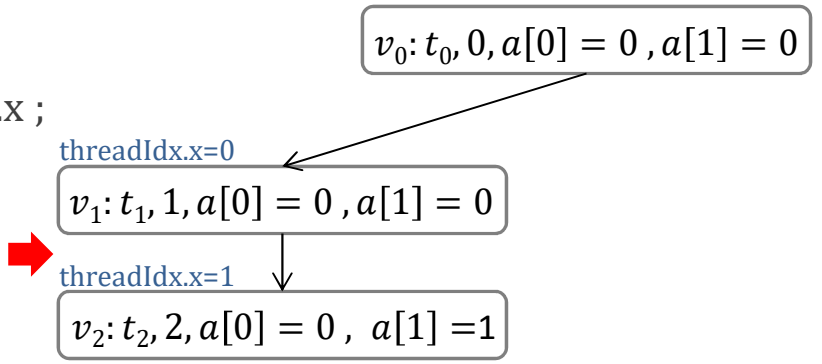

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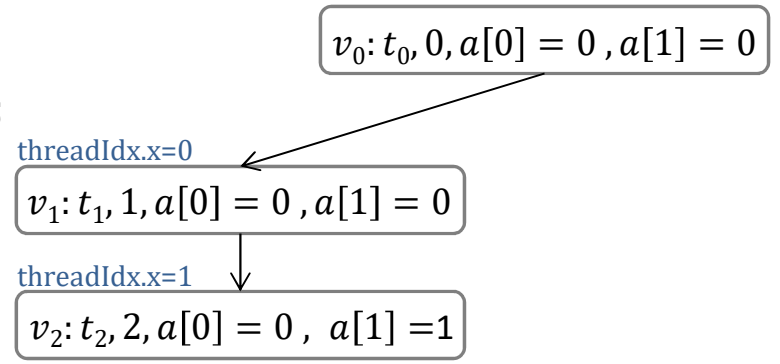

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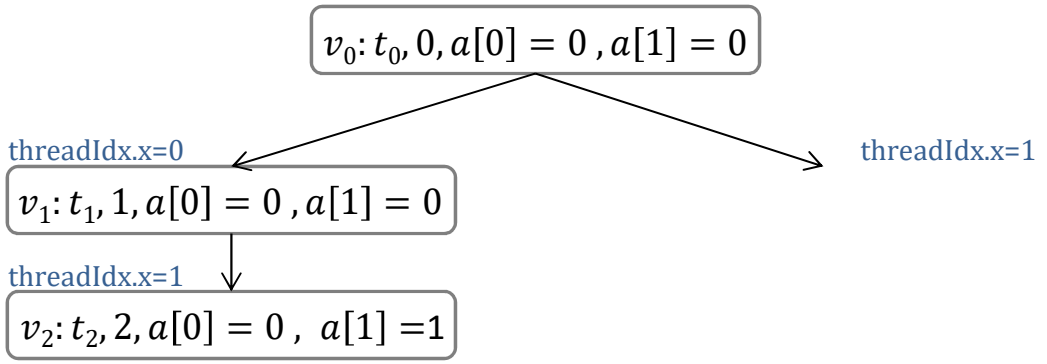

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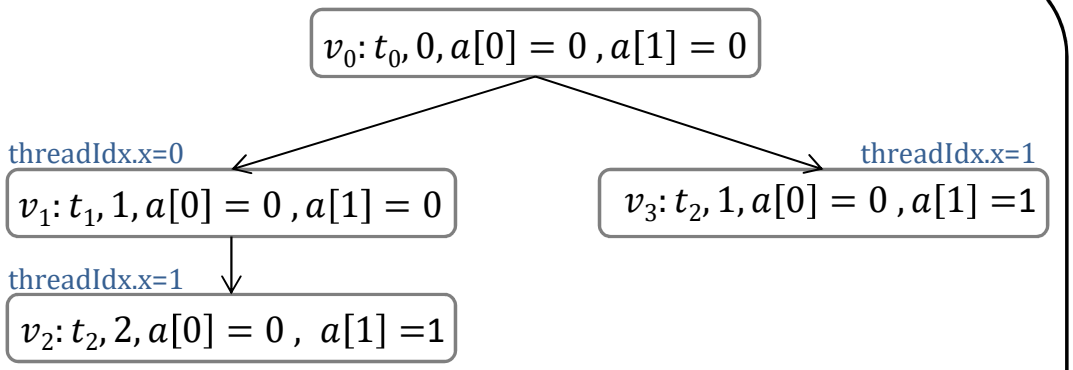

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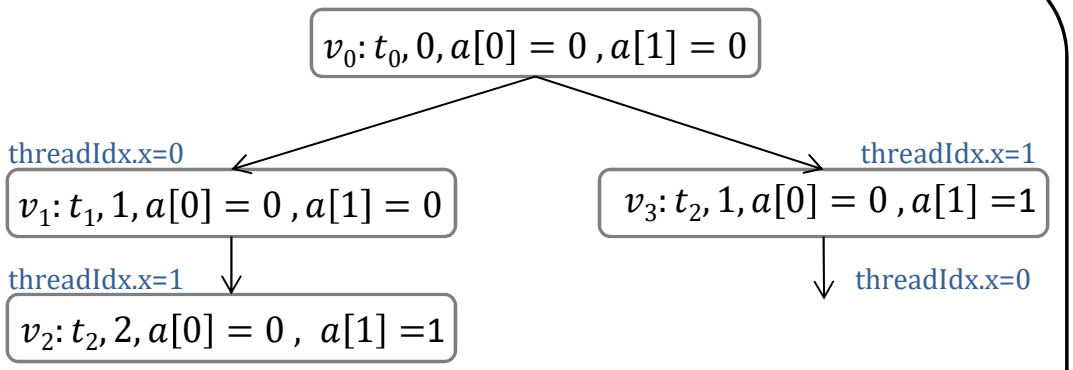

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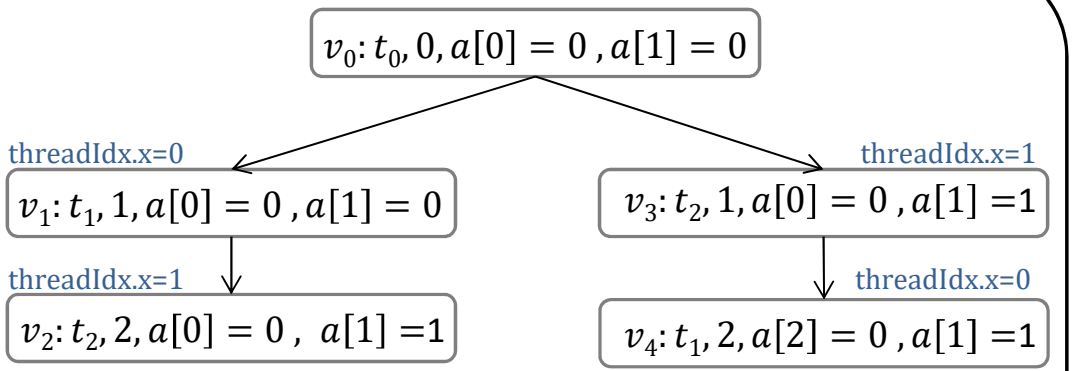

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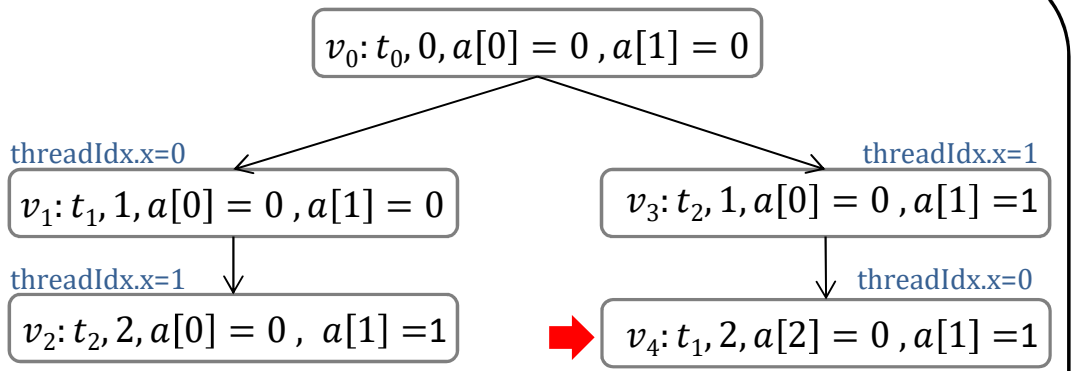

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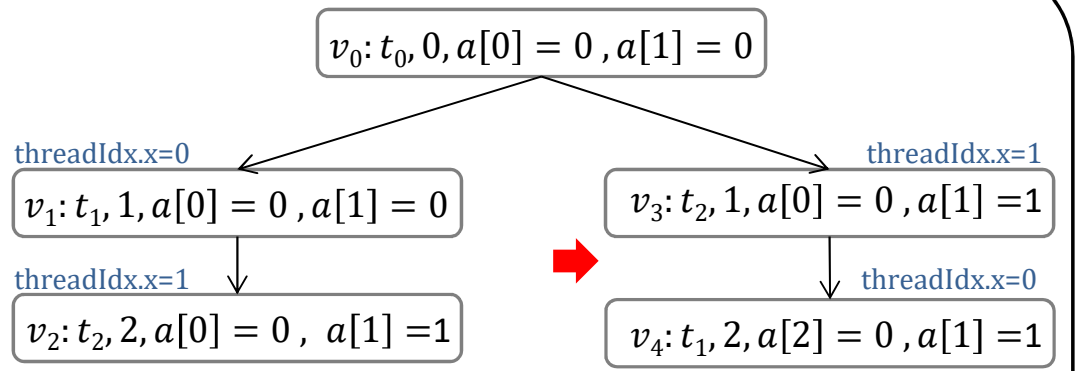

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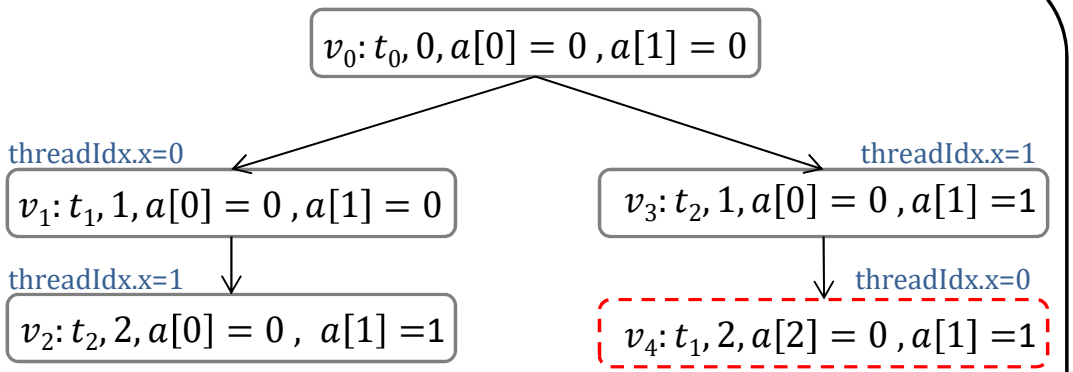

$t_1 \rightarrow t_2$ computes a different state of $t_2 \rightarrow t_1$, resulting in dependent transitions

Two-threads Analysis

- Reduction for two-threads during the program verification

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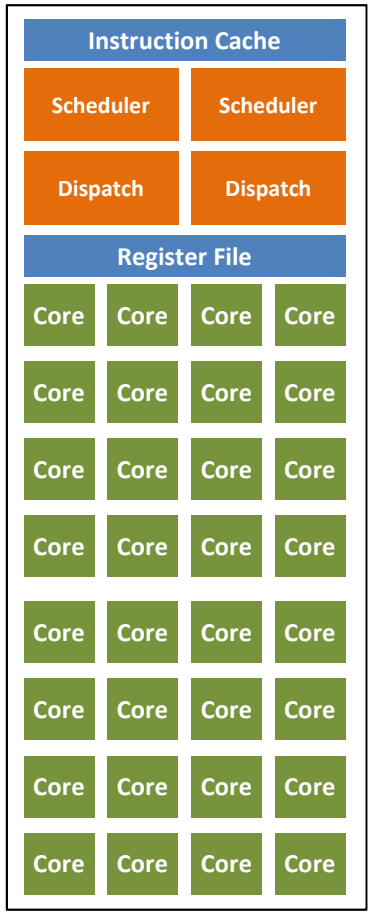
    - ➢ This proposition holds due to the GPU architecture
  - This technique is also used by other GPU kernel verification tools (*e.g.,* GPUVerify and PUG)

Two-threads Analysis in Fermi

Fermi - Stream Multiprocessor



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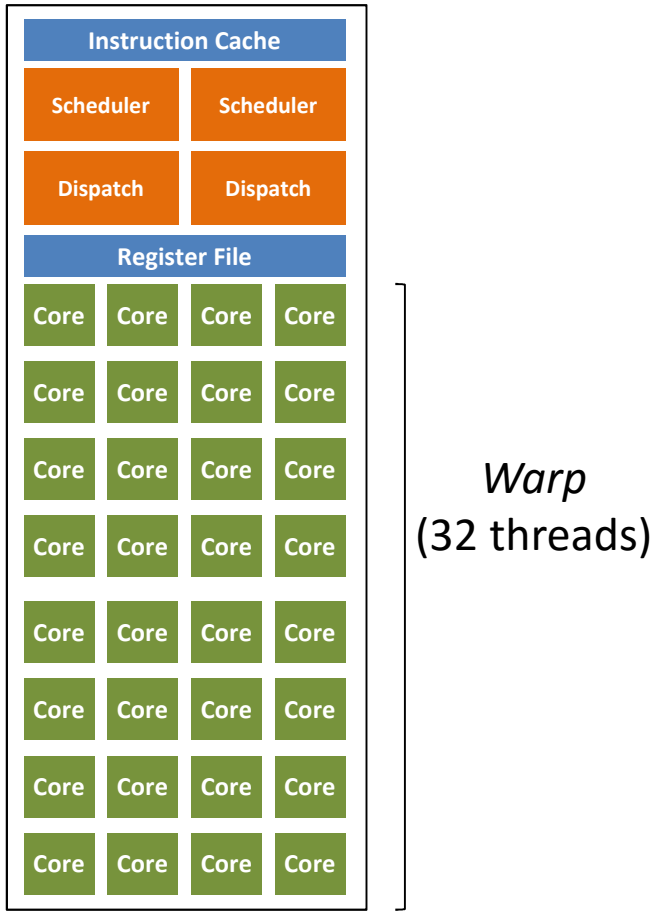
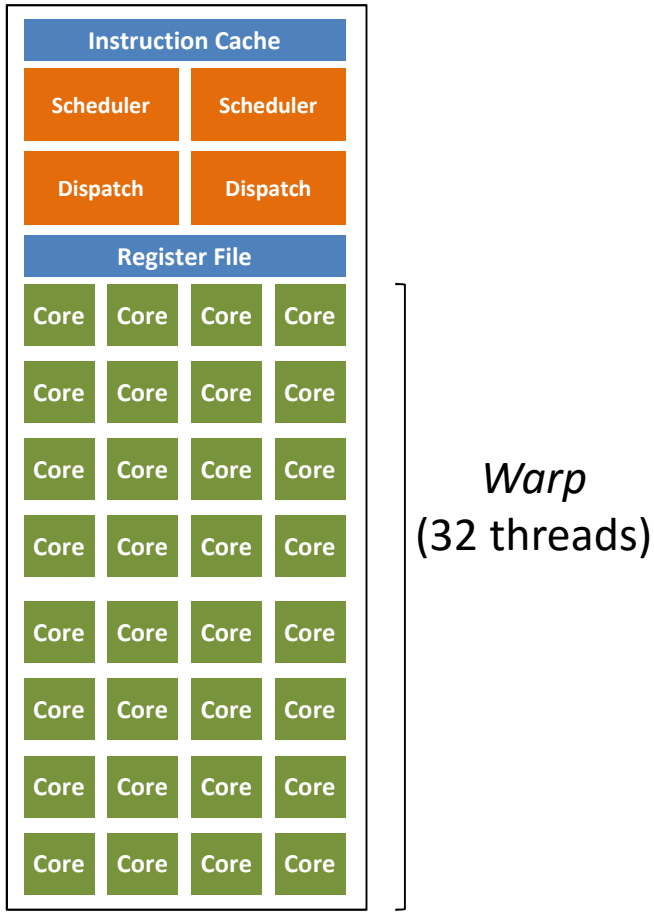
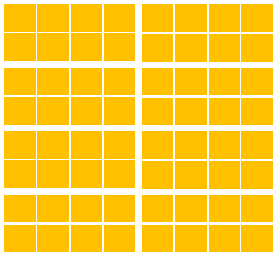


Two-threads Analysis in Fermi

Fermi - Stream Multiprocessor



Block of threads
(64 threads)



Warp
(32 threads)

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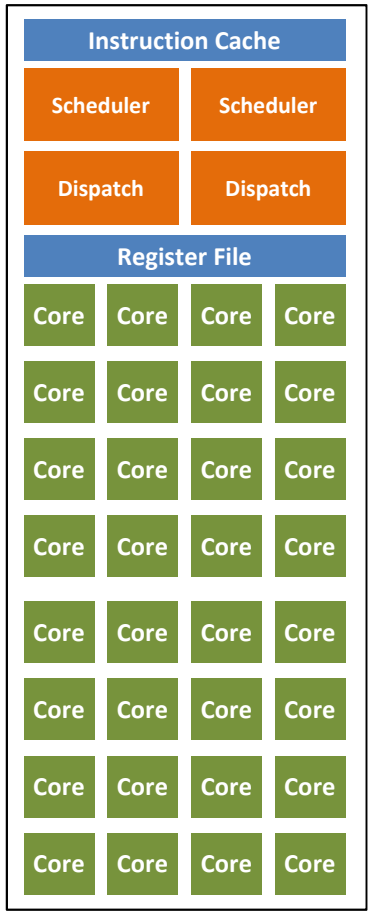

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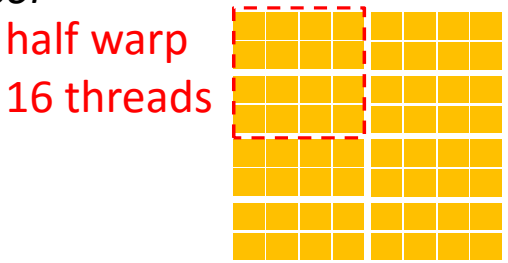

One thread group is processed by a half warp in the SM

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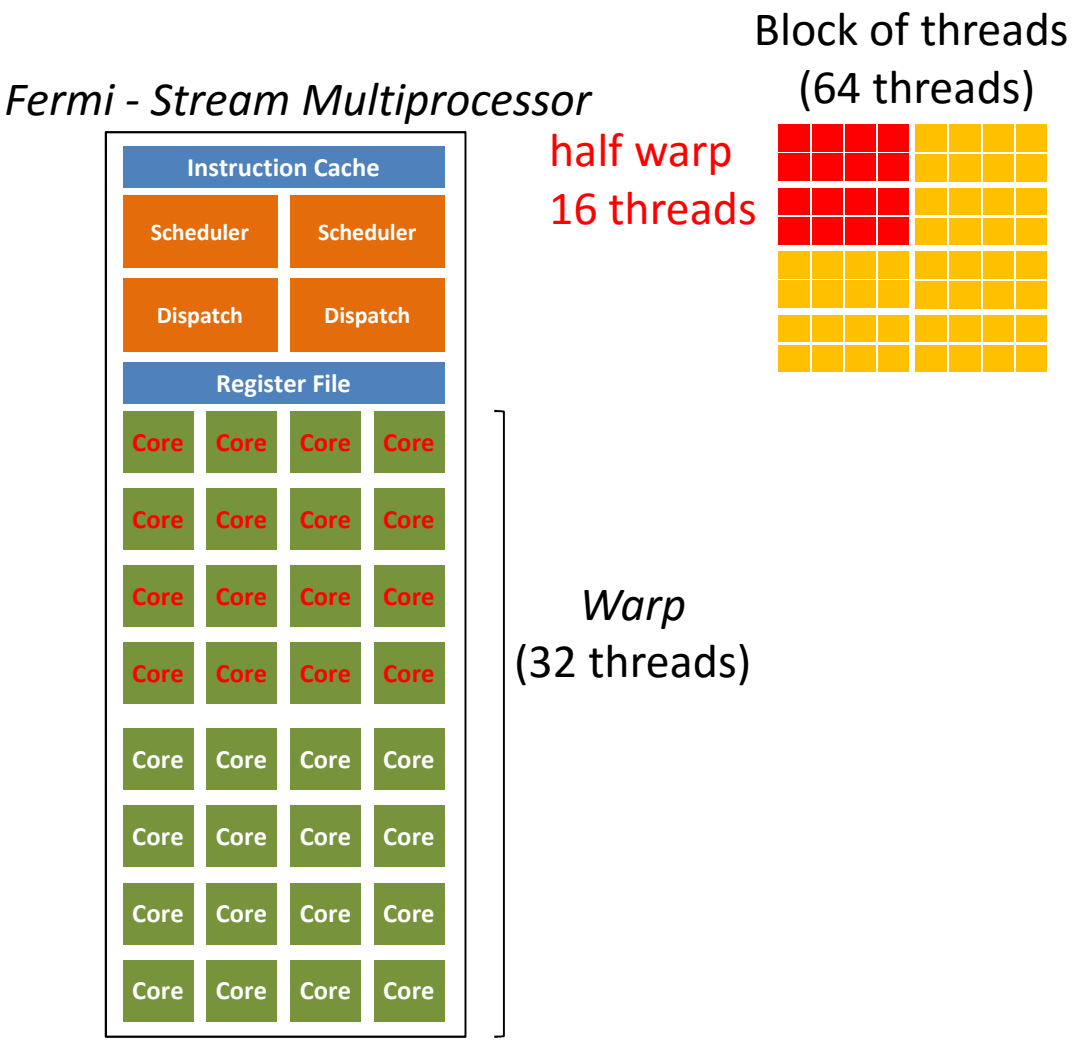

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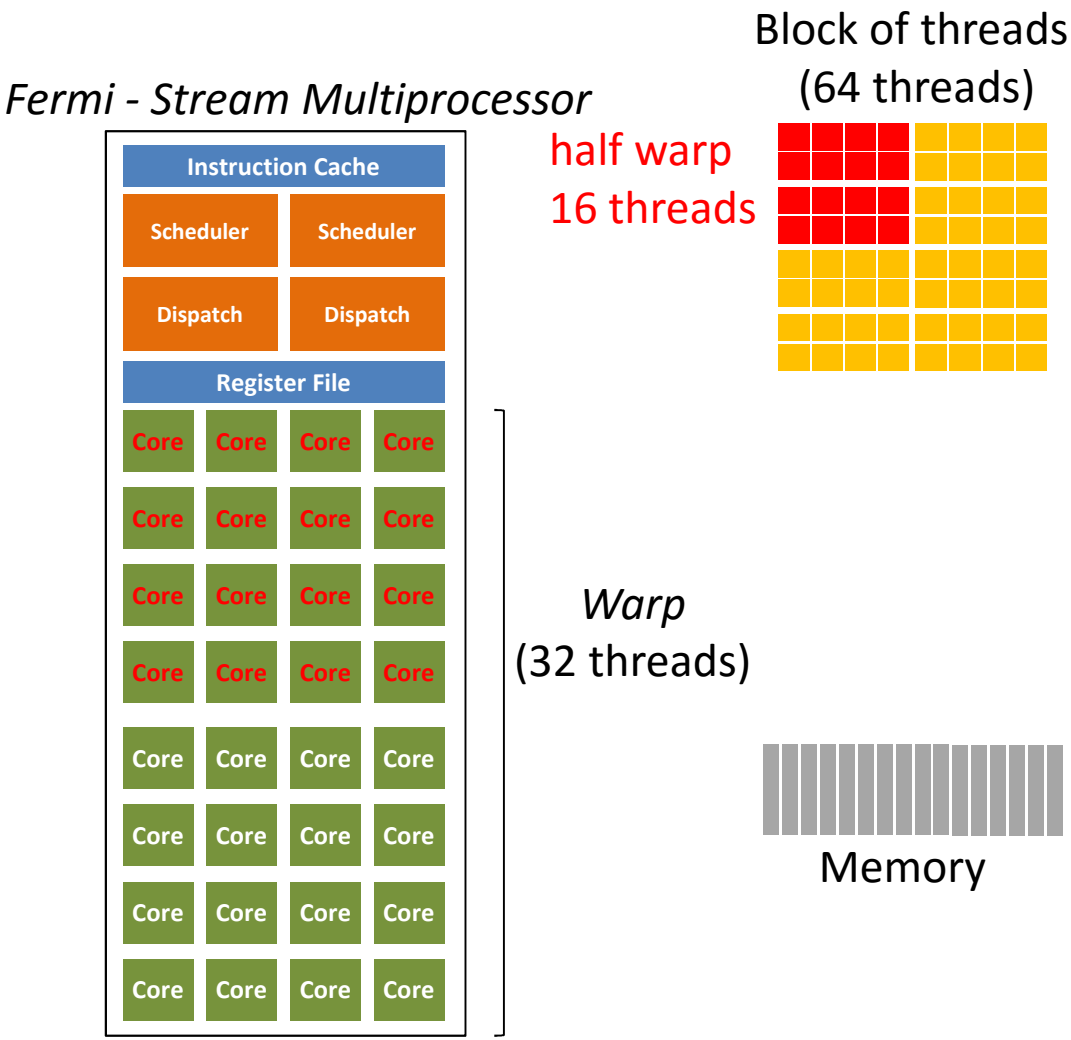

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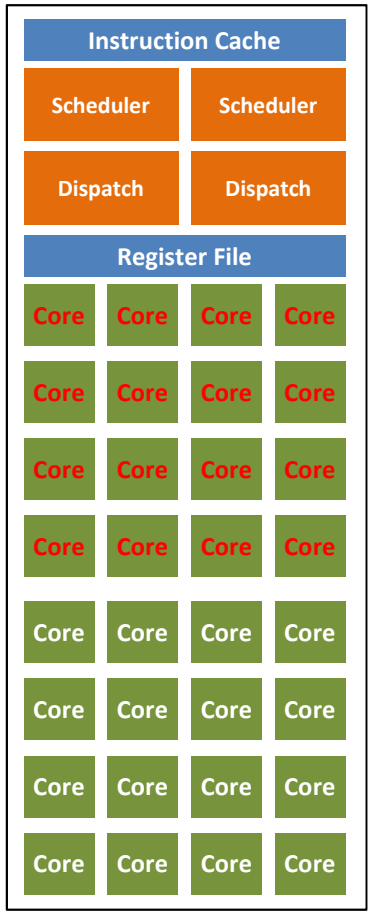

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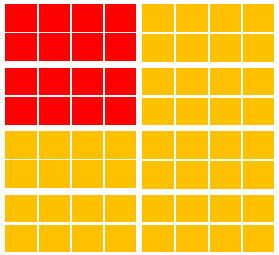
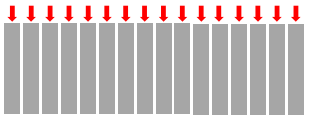


half warp
16 threads

Warp
(32 threads)



Memory

there is no data race to access different memory positions

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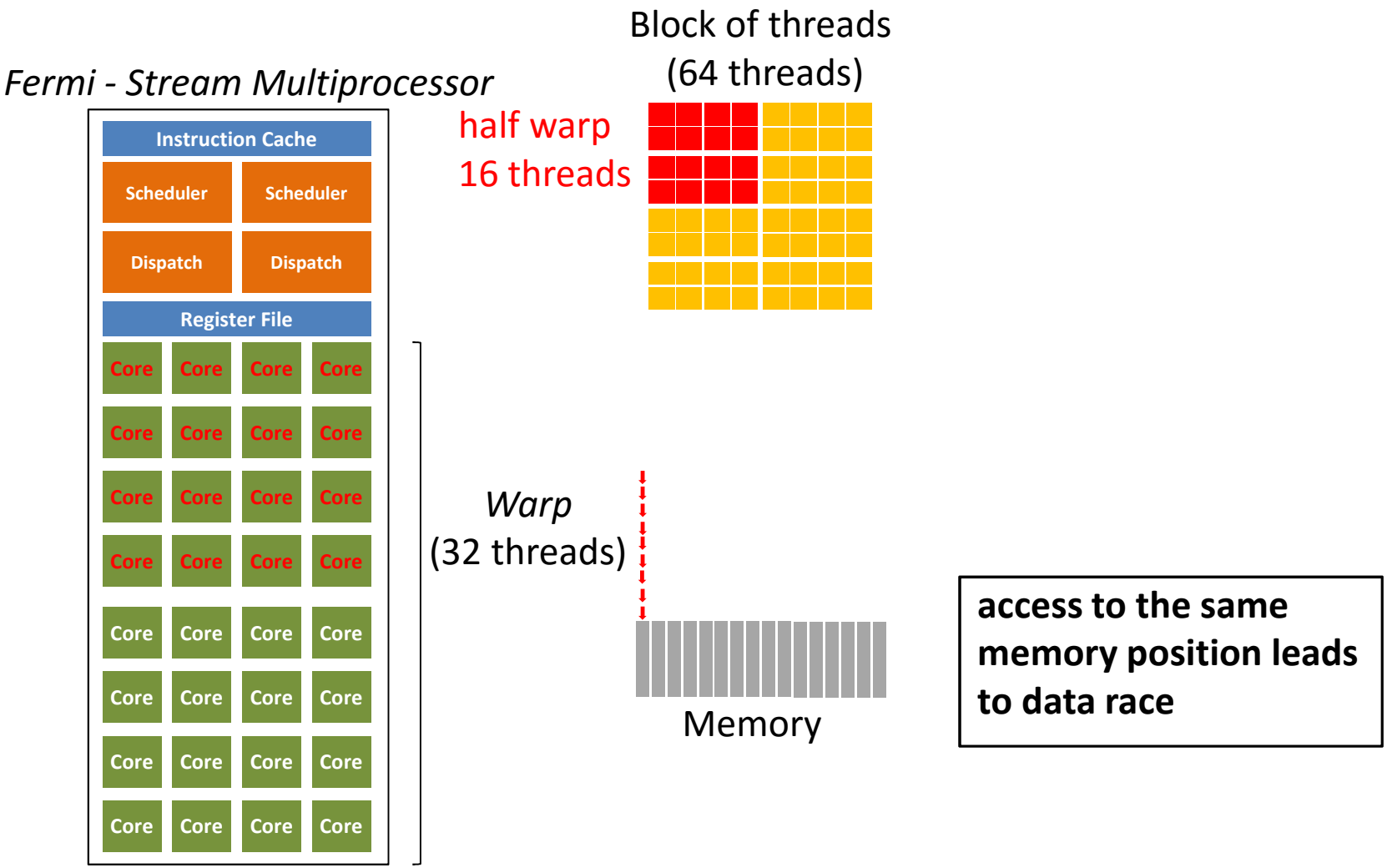

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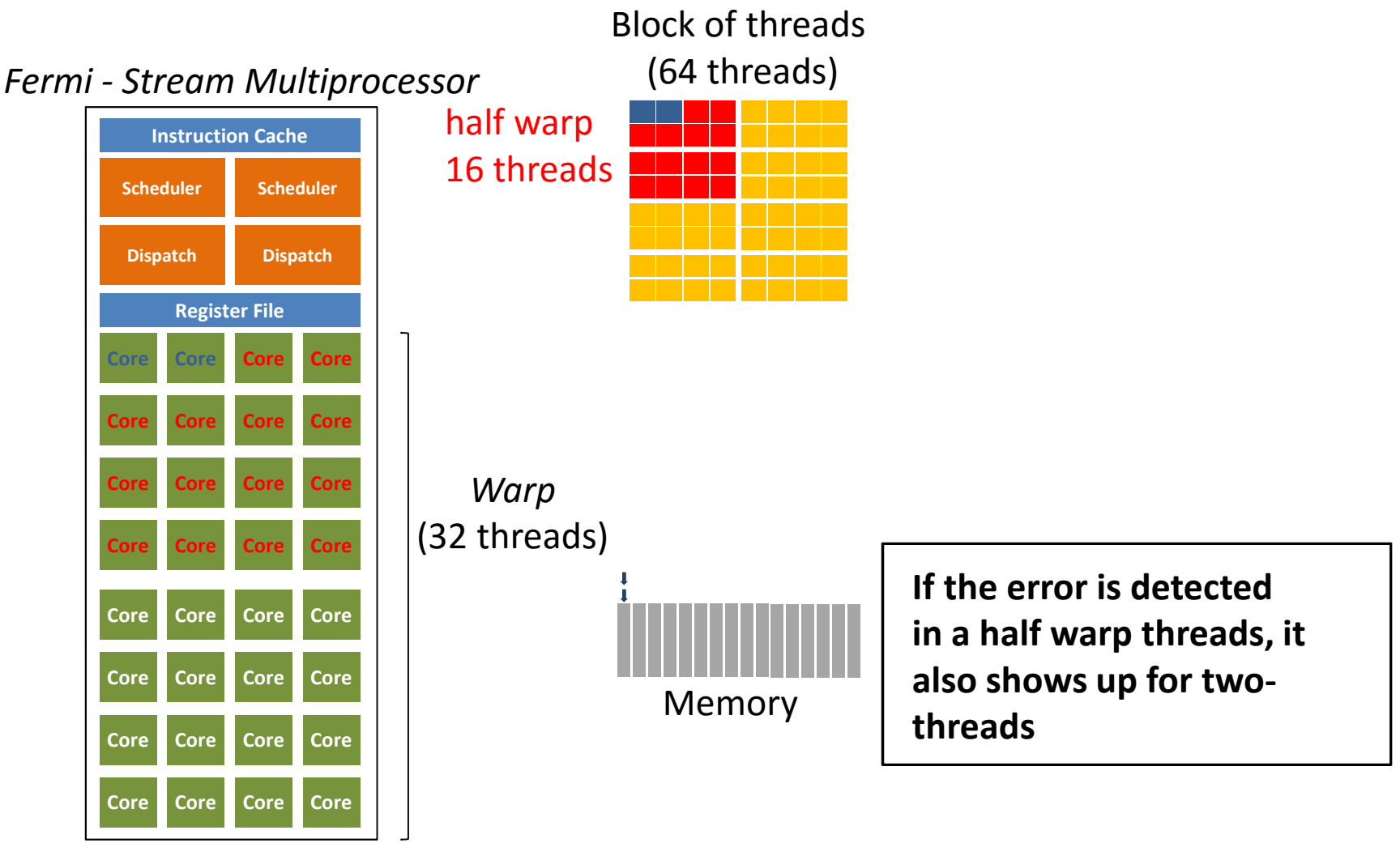

Experimental Evaluation

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- Standard PC desktop, time-out 900 seconds

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  - CUDA intrinsic variables (*e.g., uint4*)

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  - symbolic execution, POR, and GPU threads with Pthread

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**
False Incorrect	**3**	7	8	11	**3**
Not supported	**23**	24	49	82	104
Time(s)	811	128	147	**12**	158

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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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Total number of benchmarks in which the error in the program was found and an error path was reported

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

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[illegible]	[illegible]	[illegible]	8	11	**3**
[illegible]	[illegible]	[illegible]	49	82	104
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Total number of benchmarks in which the program had an error but the verifier did not find it

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CIVL did not present any "True Incorrect" result

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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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Total number of benchmarks which are not supported by the tool

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ESBMC-GPU supports the largest number of benchmarks

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

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