Strengthening Induction-Based Race Checking with Lightweight Static Analysis

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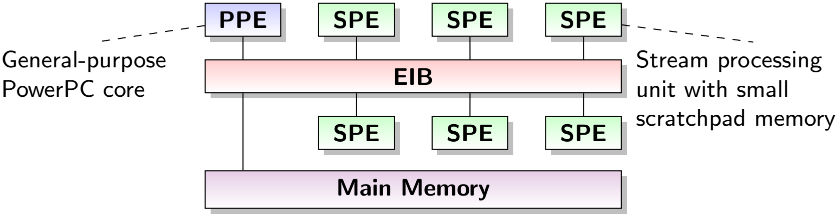
Cell BE processor



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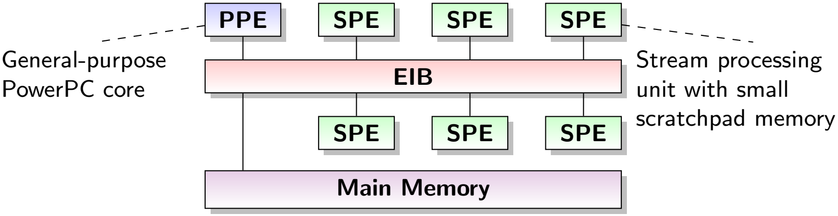

SPE cores have small (kb) and very fast scratchpad memory, to which they have exclusive access.

- SPE cores cannot not directly access main memory.
- DMA (direct memory access) library calls move data to and from scratchpad *asynchronously*

Problem

- Scratchpad memories lead to high performance
  - this comes at the expense of program complexity!
- **Massive** scope for errors with DMA operations due to possible race conditions

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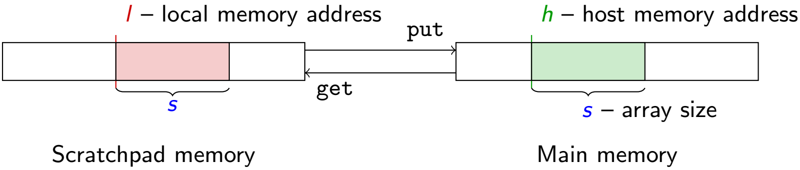
Contribution

- We apply k-induction to DMA programs to verify absence of DMA races.
- k-induction alone is too weak to verify all properties of interest.
- We strengthen k-induction using lightweight static analysis techniques

DMA operations

DMA requests are issued using library function calls:

$\texttt{get}(l, h, s, t)$ – load data into scratchpad memory
$\texttt{put}(l, h, s, t)$ – write data into main memory
$\texttt{wait}(t)$ – wait for all ops with tag t to finish



- Many concurrent DMAs can be issued simultaneously
- Latency can be hidden by using multiple buffers

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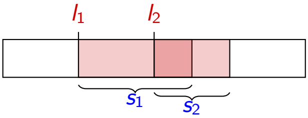
  put(l_2, h_2, s_2, t_2);

  get(l_1, h_1, s_1, t_1);



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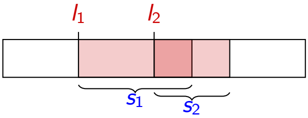

- Races between a DMA operation and local data access;

```
int a[10];
get(&a,h,10*sizeof(int),t);
a[0]=10;
```

Triple buffering code example

```
#define CHUNK 16384 // Process data in 16K chunks
float buffers[3][CHUNK/sizeof(float)]; // Three buffers for triple buffering

void process_data(float* buf) { ... }

void triple_buffer(char* in, char* out, int num_chunks) {
  unsigned int tags[3] = { 0, 1, 2 }, put_buf, get_buf, process_buf;
  get(buffers[0], in, CHUNK, tags[0]);
  in += CHUNK;
  get(buffers[1], in, CHUNK, tags[1]);
  in += CHUNK;
  wait(tags[0]);
  process_data(buffers[0]);
  put_buf = 0; process_buf = 1; get_buf = 2;
  for(int i = 2; i < num_chunks; i++) {
    put(buffers[put_buf], out, CHUNK, tags[put_buf]);
    out += CHUNK;
    get(buffers[get_buf], in, CHUNK, tags[get_buf]);
    in += CHUNK;
    wait(tags[process_buf]);
    process_data(buffers[process_buf]);
    int tmp = put_buf; put_buf = process_buf;
    process_buf = get_buf; get_buf = tmp;
  }
  ... // Handle data processed/fetched on final loop iteration
}
```

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    int tmp = put_buf; put_buf = process_buf;
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```

Buffers change roles in each iteration.

Illustration of bug

get	buffers[0]	in	CHUNK	tags[0]
get	buffers[1]	in	CHUNK	tags[1]
wait				tags[0]
process	**buffers[0]**			
Loop head				
put	buffers[0]	in	CHUNK	tags[0]
get	buffers[2]	in	CHUNK	tags[2]
wait				tags[1]
process	**buffers[1]**			
Loop head				
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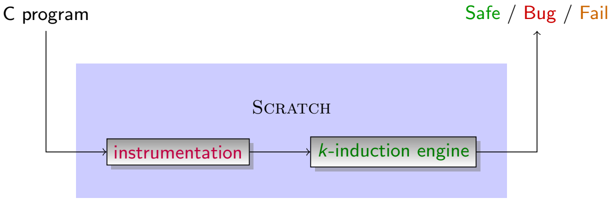
Loop head				
put	buffers[1]	in	CHUNK	tags[1]
get	buffers[0]	in	CHUNK	tags[0]

Race on buffers[0]

Asserting race-freedom with SCRATCH



- Establishes race freedom for code running on a single SPE node.
- Based on the CBMC bounded model checker
- Calls to `put`, `get`, and `wait` are instrumented with assertions.
- The resulting program is analyzed with a *k*-induction engine.

Instrumenting DMA programs

Add a tracker datastructure:

```
struct DMA_op {
  bool     valid;
  char*   address;  // Local store address
  unsigned size;     // Num bytes to transfer
  unsigned  tag;      // Identifying tag

};

struct DMA_op tracker = { 0, *, *, * };
```

Used to store one single pending DMA request.

Instrumenting DMA programs

A call get(l, h, s, t) is translated to:

```
assert(t < 32);              // Check tag in range
assert(s < 16K);             // Check DMA not too large
assert(!tracker.valid        // Check no race with prior DMA
     || l + s <= tracker.address
     || tracker.address + tracker.size <= l);
memset(l, *, s);             // Over-approximate effect of DMA

if(*) {
  tracker.valid = true;      // Nondeterministically decide
  tracker.address = l;       // whether to track this DMA
  tracker.size = s;
  tracker.tag = t;           // Model checker will try both
}                            // possibilities!
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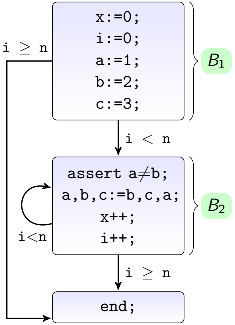
The resulting program is checked using k-induction.

k-Induction example



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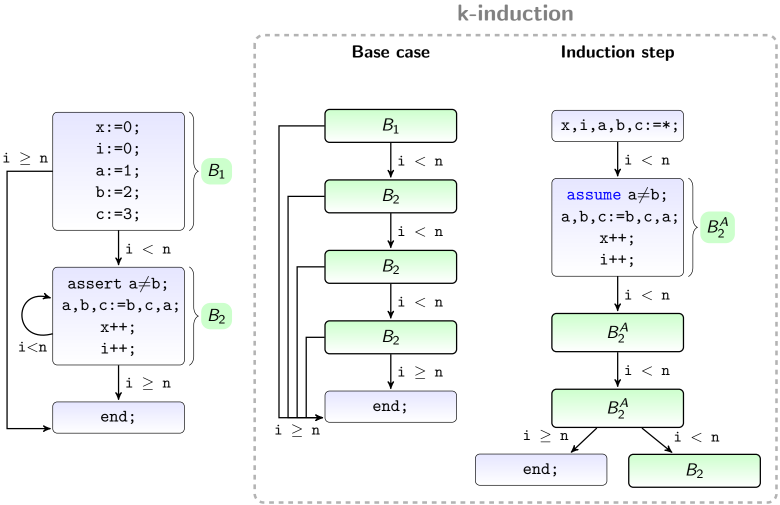

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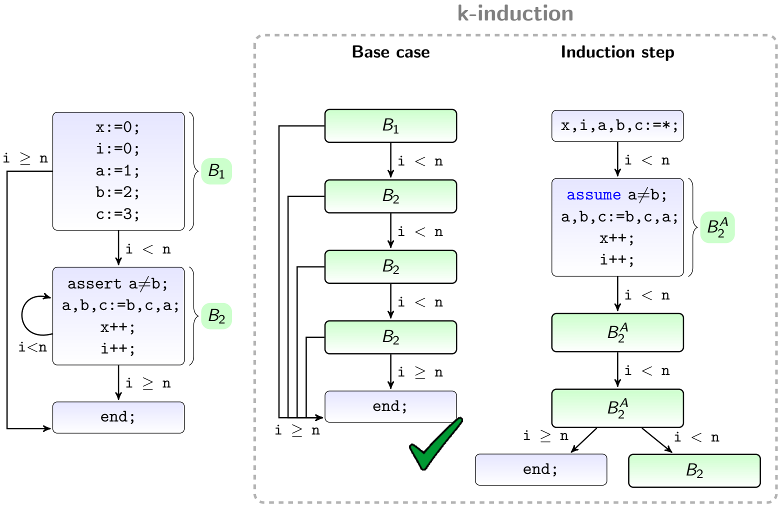

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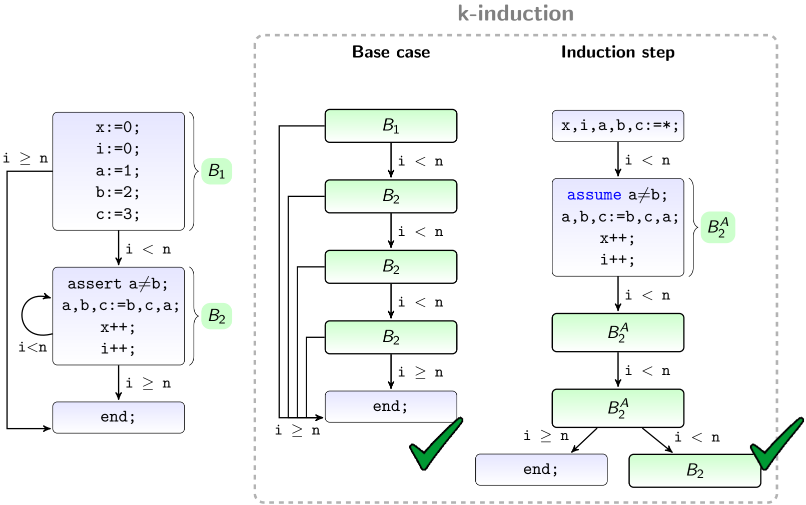

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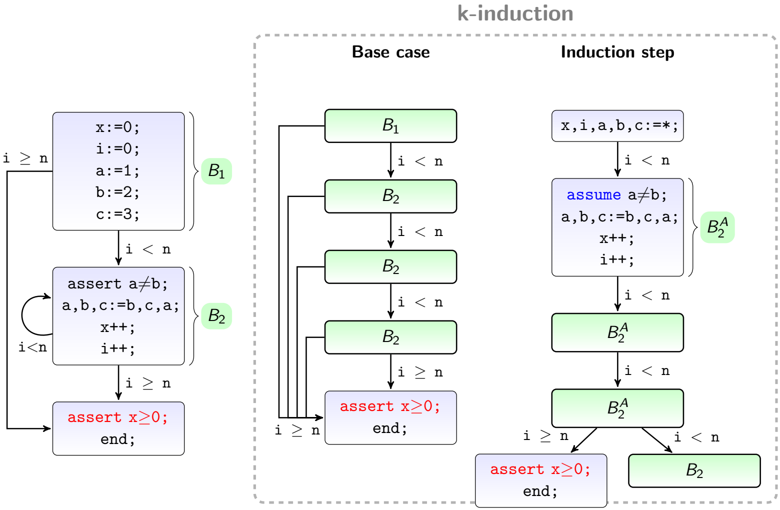

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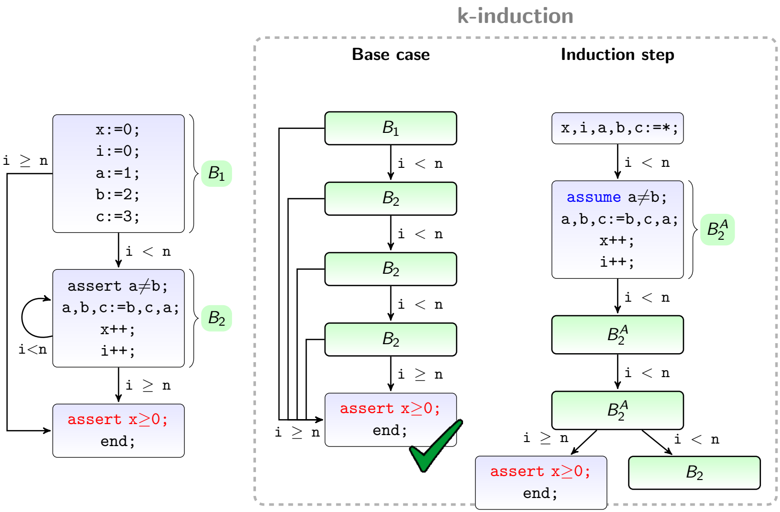

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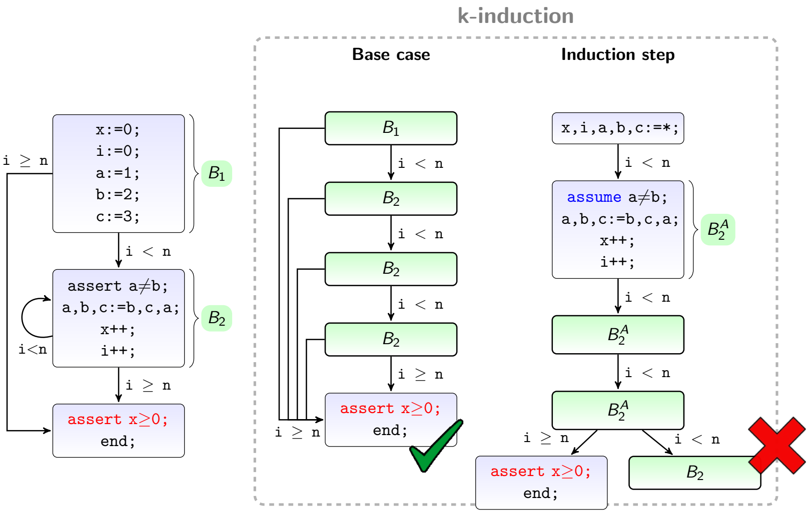

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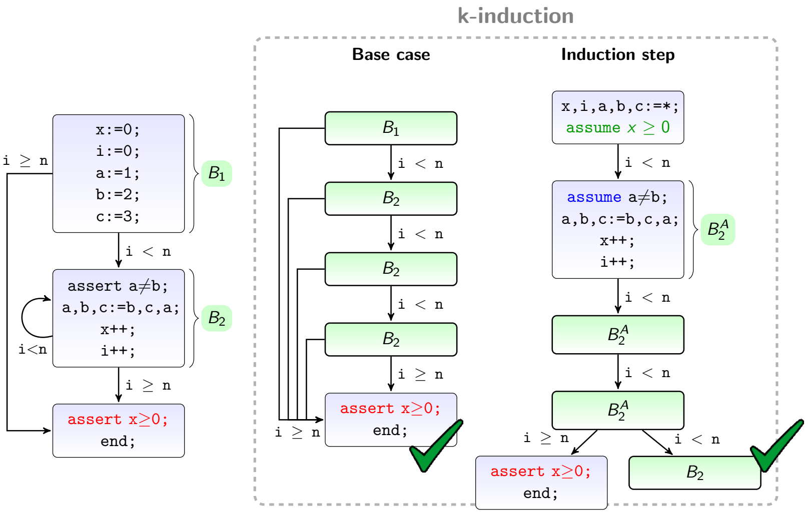

k-Induction for software

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- Base case failure: There is a bug of depth at most k
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But as we have seen this is not always enough!

Strengthening k-induction

Transition system $M = (S, T, I)$. Set of error states E.

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***k*-induction**
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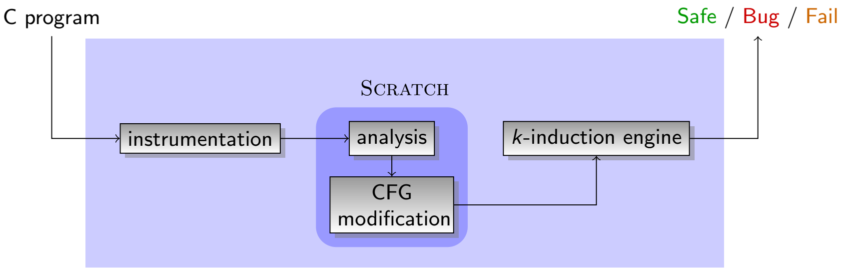
Strengthening induction-based race checking

Analysis step is added to the scratch pipeline:



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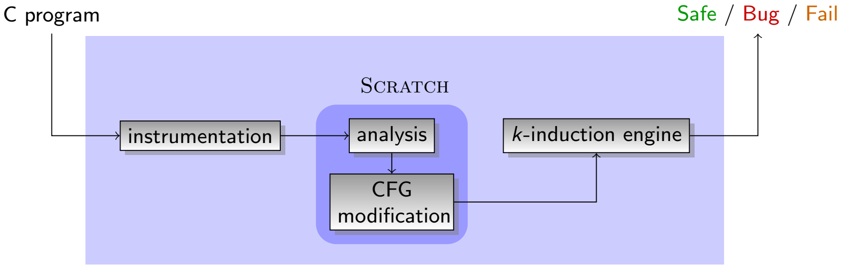

For modifying the CFG, we utilize

- Analysis with cheap abstract domains
- Code motion
- Assertion chunking

Abstract Domains

We utilize a *reduced product* of two domains:

- the interval domain; $x \in [c_1, c_2]$
- an equality / disequality domain; $x = y$, $x \neq y$

Then annotate CFG with assumptions

$$inv\text{: control flow locations} \rightarrow \text{local invariants.}$$

- Prepend control flow nodes with `assume` statements:

$$\begin{array}{lcl} l_1 : \texttt{s1;} & & \texttt{assume(}inv(l_1)\texttt{); s1;} \\ l_2 : \texttt{s2;} & \longrightarrow & \texttt{assume(}inv(l_2)\texttt{); s2;} \\ l_3 : \texttt{s3;} & & \texttt{assume(}inv(l_3)\texttt{); s3;} \\ l_4 : \texttt{s4;} & & \texttt{assume(}inv(l_4)\texttt{); s4;} \end{array}$$

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Strengthening `assert` statements can help the inductive step of the proof.

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Code motion is used to reverse this process.

```
get(l,h,s,t);
s2;
while(...)
{...}
s3;
```

→

```
get_possible(l,h,s,t);
s2;
while(...)
{...}
get(l,h,s,t);
s3;
```

- Swap independent statements to push back DMA operations.
- Insert check at original location (non-terminating loops!)
- Soundness of statement independence is checked using a SAT solver.

Experiments

Runtimes on a 3.2Ghz Intel Xeon 48GB:

Benchmark	**Lines of code**	**Time**	**of which AI**	k	**Max base case vars**	**Max step case vars**
single buffer	152	1.70	9.86%	2	5873	178305
single buffer IO	160	4.25	5.21%	3	6781	334915
double buffer	270	8.52	9.06%	2	67418	386705
double buffer IO	284	24.74	3.49%	3	132266	726512
triple buffer	379	44.32	6.46%	3	9208	650404
triple buffer IO	420	54.80	3.96%	3	9224	707592
double buffer TP	359	9.13	15.65%	2	109783	206434
double buffer IO TP	390	42.47	7.18%	3	215385	854164
triple buffer TP	611	138.10	7.13%	3	8813	958183
triple buffer IO TP	1813	422.45	3.39%	3	8824	3377134

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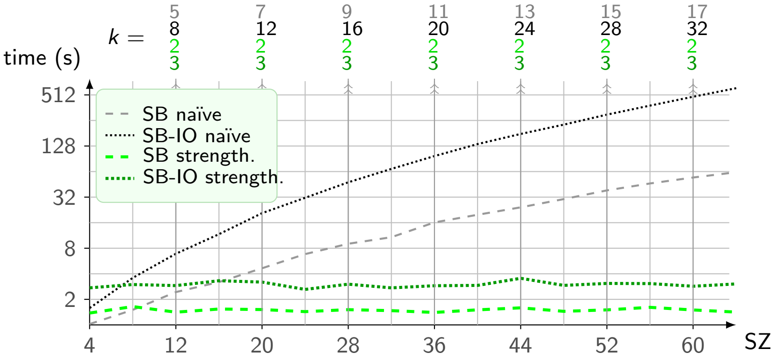
- k-induction works well for sequential hardware circuits with pipelines.
  - required k proportional to pipeline depth
- Buffering schemes used in DMA programs have a similar structure.
  - required k proportional to number of buffers

Effect of strengthening on k-induction

- Benchmarks cannot be verified without strengthening.
- To enable comparison, we verify simplified example programs, by restricting the size of the data buffer SZ.



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Future work includes:

- Inter-thread race detection
- Widening the scope of *k*-induction beyond race checking

Thank you for your attention.