CIVL The Concurrency Intermediate Verification Language

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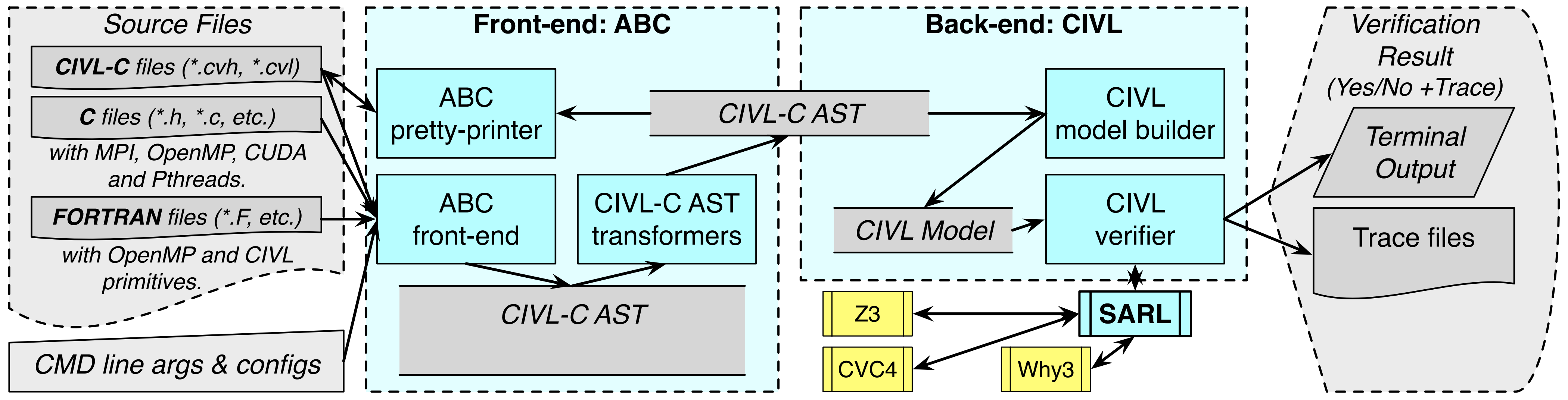
http://civl.cis.udel.edu/app/

1. Abstract

- CIVL: Concurrency Intermediate Verification Language
- Verify correctness of Scientific Computing applications
- Supported languages: **C, Fortran** (work in progress)
- Supported Parallelism: **OpenMP, MPI, CUDA, Pthreads**
- Everything is translated to the intermediate language **CIVL-C**
- Verification techniques: model checking, symbolic execution
- Compare two programs, for example:
  - before / after refactoring
  - before / after parallelization or performance tweaks
- Compare to formal specification
- Find inputs that trigger bugs, for example deadlocks, race conditions, assertion violations, illegal pointer dereferences, memory leaks, division by zero, out-of-bound array indexing
- Assumes real arithmetic, no model for roundoff errors. But: still useful to distinguish roundoff from other sources of error.



2. CIVL-C Language

- CIVL-C: intermediate language embedded in sequential C
- Concurrency and verification primitives
- Functions can be spawned as processes
- Nested function definitions in any scope
- With this, CIVL-C can represent semantics of message passing and shared memory parallelism

Examples of CIVL-C primitives:

$input: type qualifier for read-only global variables initialized with unconstrained values;
$output: type qualifier for write-only global variables as outputs;
$assume(*expr*) : statement informing the verifier to ignore the current execution unless *expr* holds;
$assert(*expr*) : checks that *expr* holds and reports error if it does not;
$forall {*T* i | *cond* } expr** : universal quantification; **$exists {*T* i | *cond* } *expr* is similar;
$choose {*stmt0 stmt1* … }: non-deterministic selection of one enabled statement;
$spawn *f* (*arg0*, …) : creates a new process executing function *f* ;
$when(*guard*) *stmt* : guarded command; enabled only when *guard* evaluates to true;
$atomic *stmt* : executes *stmt* without interleaving of other processes.

3. A CIVL Example

```c
// dot_product.c
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
  int i, n;
  float a[8], b[8], sum;

  n = 8;

#pragma omp parallel for
  for (i = 0; i < n; i++) {
    sum = sum + (a[i] * b[i]);
    printf("loop %d\n", i);
  }
  printf("  Sum = %f\n”, sum);
}
```

- C/OpenMP program computing a dot product
- Data-race caused by missing reduction clause
- CIVL detects the data race on the variable sum
- The error message reported by CIVL shown below
- CIVL is able to generate a minimal counterexample for every defect found. which is useful for defects that are only triggered by a specific input.

```
CIVL v1.19 of 2019-02-08 – https://vsl.cis.udel.edu/civl
  ...
Thread 1 can not safely read memory location &<d5>sum, because thread 0 has
written to that memory location and hasn’t flushed yet.

Violation 0 encountered at depth 166:
CIVL execution violation in p2 (kind:ASSERTION_VIOLATION, certainty: PROVABLE)
  ...

Input:       ...
Context:     ...
Call stacks: ...

=== Source files ===
dot_product.c

=== Command ===
civl verify –input_omp_thread_max=2 dot_product.c

=== Stats ===
  ...

=== Result ===
The program MAY NOT be correct. See CIVLREP/dot_product_log.txt
```

4. CIVL Transformations

CIVL performs a sequence of transformations to build a pure CIVL-C AST merged from multiple translation units written in C, CIVL-C or Fortran language. Side-effect expressions and parallel dialects are transformed to functionally equivalent CIVL-C code. There is also a transformer that simplifies OpenMP programs using static analysis techniques.
Four transformation examples are given below:

4.1 MPI Transformation

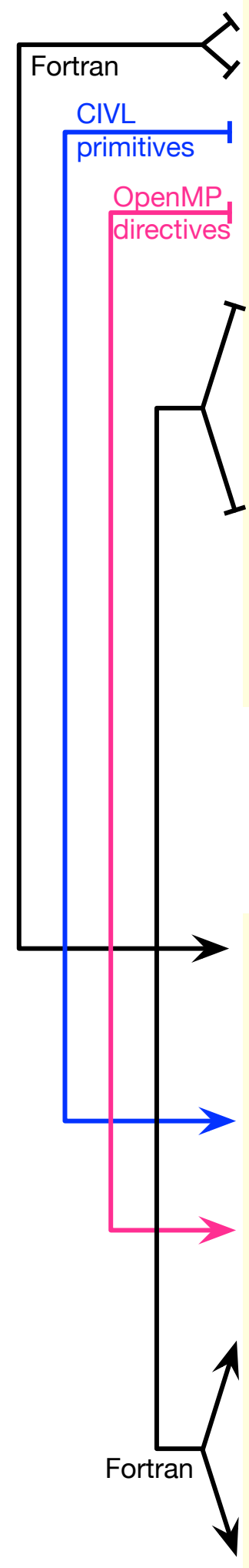
```c
$input int _mpi_nprocs;
$input int _mpi_nprocs_lo, _mpi_nprocs_hi;
$assume(_mpi_nprocs_lo <= _mpi_nprocs &&
      _mpi_nprocs <= _mpi_nprocs_hi);
$mpi_gcomm _mpi_gcomm =
      $mpi_gcomm_create($here, _mpi_nprocs);

void _mpi_process(int _mpi_rank) {
  MPI_Comm MPI_COMM_WORLD =
    $mpi_gcomm_create($here, _mpi_gcomm, _mpi_rank);
  /* ⟨ external–definitions ⟩ */
    ...
  int _gen_main(void) { ... } _gen_main(); //main func
  $mpi_gcomm_destroy(MPI_COMM_WORLD);
}

void main() {// This is the root process marked as p0
  $parfor (int i : 0 .. _mpi_nprocs–1)
    _mpi_process(i);
  $assert($forall (int i: 0..N–1)
    $mpi_gcomm_destroy(_mpi_gcomm);
}
```

A C/MPI program is automatically translated into the CIVL-C code shown above. The commented root process starts *`_mpi_nprocs`* CIVL processes. Each *`_mpi_process`* executes the original *`main`* function by calling *`_gen_main`*. Buffered messages are stored in a global communicator *`_mpi_gcomm`*.

```c
int main(void)
{ ... } //main func
```

4.3 Fortran Transformation

```fortran
      subroutine mxf1(a,n1,b,n2,c,n3)
        real a(n1,1), b(1,n3), c(n1,n3)
C$CVL $assert(n2 == 1);
C$OMP parallel default(shared) private(i,j,k)
C$OMP do
        do j=1,n3
          do i=1,n1
            c(i,j) = a(i,1)*b(1,j)
          ENDDO
        ENDDO
C$OMP end do
C$OMP end parallel
      end
```



ABC translates a Fortran program with OpenMP and CIVL-C primitives into a CIVL-C AST, which can be printed as a CIVL-C program.

```c
void MXF1(double A[][], int* N1, double B[][],
    int* N2, double C[][], int* N3) {
  int I; int J;
  $assert((*N2) == 1);
  #pragma omp parallel
  {
    #pragma omp for
    for (J = 1; J <= (*N3); J +=1 )
      for (I = 1; I <= (*N1); I += 1)
        C[J–1][I–1] = A[1–1][I–1]*B[J–1][1–1]
      }
    }
  }
}
```

4.2 OpenMP Simplification

CIVL combines several kinds of static analysis to determine if a parallelized OpenMP code is functionally equivalent to a sequentialized version of itself.
For two concurrent iterations `i` and `i′`, the OpenMP construct *`simd`* with *`safelen(8)`* clause shown below guarantees that:

$$i \neq i' \text{ and } |i - i'| < 8$$

```c
#include <assert.h>

int main() {
  int a[32], b[16];
  int *p0, *p1, *p2;

  p0 = a; p1 = p0+16; p2 = b;
#pragma omp simd safelen(8)
  for (int i=0; i<8; i++) {
    p0[i] = 1; p0[i+8] = 1;
    p1[i] = 1; p1[i+8] = 1;
    p2[i] = 2; p2[i+8] = 2;
  }
  // Check the correctness
  for (int i=0; i<32; i++)
    assert(a[i] == 1);
  for (int i=0; i<16; i++)
    assert(b[i] == 1);
}
```

Points-to Analysis

```
p → a[0],
q → a[16],
r → b[0]
```

Read/Write Analysis

read/write objects:

```
p[i]   : a[i],
p[i+8] : a[i+ 8],
q[i]   : a[i+16],
q[i+8] : a[i+24],
r[i]   : b[i],
 …
```

Dependency Analysis

```
a[i] indep-of a[i′],
a[i] indep-of a[i′+ 8],
a[i] indep-of b[i′],
 …
```

4.4 Comparison Combination

```c
//spec
$input int IN, K=3;
$assume(0 < IN);
$output int OUT;

int main() {
  OUT = IN*K;
}
```

CIVL proves the functional equivalence between a specification program (spec) and an implementation one (impl) by checking their output variables.
Two given programs are combined into a single one and the comparison is checked by equality assertions for each pair of output variables.

```c
//impl
$input int IN, K=3;
$output int OUT;

int main() {
  int sum = 0;
  int i = 0;
  for(; i < K; i++)
    sum = sum + IN;
  OUT = sum;
}
```

```c
$input int N, K=3;
$output int OUT_spec;
$output int OUT;

int $system_spec() {
  $assume(0 < IN);
  int $spec_main(void){
    OUT_spec = IN*K;
  }
  $spec_main();
}

int $system_impl() {
  int $impl_main(void){
    int sum = 0;
    int i = 0;
    for(; i < K; i++)
      sum = sum + IN;
    OUT = sum;
  }
  $impl_main();
}

int main() {
  $system_spec();
  $system_impl();
  $assert_equals(
      &OUT_spec, &OUT);
}
```

5. NUCLEI

```fortran
      do 140 loop=1,20
        do 110 i=1,lcx
          block(1)
  110   continue
        block(2)
        do 120 j=2,lcx+1
          block(3)
  120   continue
        block(4)
        if(loop.eq.1) then
          block(5)
        else
          if(cond(loop)) goto 170
          block(6)
        end if
  140 continue
  170 block(7)
```

```fortran
  flag = 0.0
  do loop=1,20
    do i=1,lcx
      block(1)
    end do
    block(2)
    do j=2,lcx+1
      block(3)
    end do
    block(4)
    if(loop.eq.1) then
      block(5)
    else
      if(cond(loop)) then
        flag = 1.0
      else
        if(flag.eq.0.0) then
          block(6)
        end if
      end if
    end if
  end do
  block(7)
```

- Nucleon matter code
- R. B. Wiringa, et al. Equation of state for dense nucleon matter. Phys. Rev. C, 38:1010–1037, 1988
- Uses several obsolescent Fortran features: shared do termination, statement functions, and fixed form source
- Original code was modified to avoid goto, exit and break statements to enable automatic differentiation using OpenAD
- Modifications were supposedly semantics-preserving
- CIVL found a bug: goto statement (left side) was incorrectly replaced with an if-block (right side)
- Currently manual Fortran to C conversion necessary.

6. FLASH

```fortran
subroutine Heat(blockCount, blockList, dt, time)
  #include "Flash.h"
  #include "constants.h"

  ! use statements
  ! type declarations ...
  ! some initializations etc.

!$omp parallel do private(n,blockID,k,j,i,solnData,dimSize, ...)
   do n = 1, blockCount
     blockID = blockList(n)
     ! Get the block distribution for each openMP thread
     call Grid_getBlkIndexLimits(blockID,blkLimits,blkLimitsGC)
     call Grid_getBlkPtr(blockID,solnData)
     dimSize(:)=blkLimitsGC(HIGH,:)–blkLimitsGC(LOW,:)+1
     do k = blkLimits(LOW,KAXIS), blkLimits(HIGH,KAXIS)
        do j = blkLimits(LOW,JAXIS), blkLimits(HIGH,JAXIS)
           do i = blkLimits(LOW,IAXIS), blkLimits(HIGH,IAXIS)
             ! Read from solnData(:,i,j,k)
             ! Calculate updates
             ! Write to solnData(:,i,j,k)
           enddo
        enddo
     enddo
     call Grid_releaseBlkPtr(blockID,solndata)
  enddo
end subroutine Heat
```

- Work in progress : verify OpenMP parallelization in Flash application.
- CIVL-C supports all features shown in this example.
- CIVL’s Fortran front-end needs to be extended further:
  - Fortran interfaces
  - Fortran pointers
  - Fortran optional arguments
  - Fortran array assignments.

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