Analysis of LLVMTA and Heptane for WCET calculation of dataflow actors

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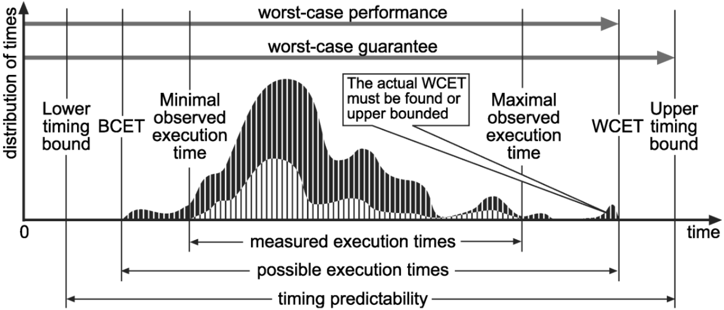
  - assess resource needs for real-time systems [2]
- For example the air bag control system in an automobile

Main WCET methods



[3]

- WCET bounds must be safe and tight

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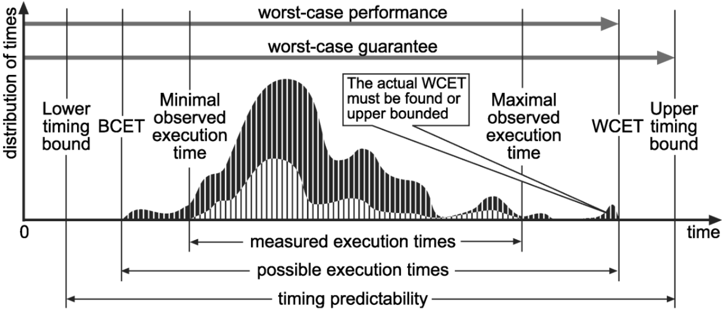

[3]

- WCET bounds must be safe and tight
- Main WCET methods are
  - Measurement analysis (optimistic, not all paths are tested)
  - Static analysis (pessimistic, worst theoretically possible WCET)

Measurement analysis

- Measurements of the basic-block execution times on the real HW processor (or a cycle-accurate simulator)
- Building of precise hardware model is not needed [4]

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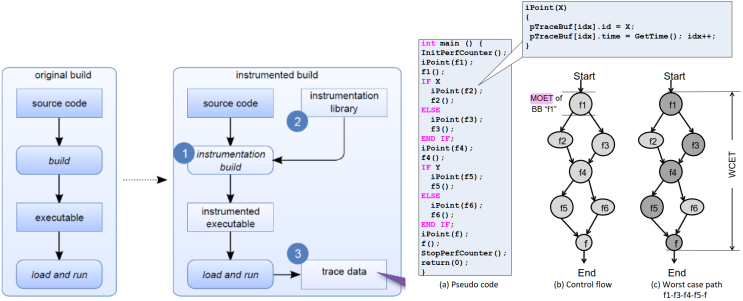
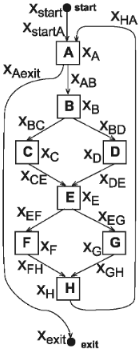


Rapitime, a commercial measurement based (hybrid) WCET tool [4]

Static analysis

1. Obtain the Control Flow Graph (CFG) and find possible paths



// Start and exit constraints

$x_{start} = 1, x_{exit} = 1$

// Structural constraints

$x_{start} = x_{startA}$

$x_A = x_{startA} + x_{HA} = x_{Aexit} + x_{AB}$

$x_B = x_{AB} = x_{BC} + x_{BD}$

$x_C = x_{BC} = x_{CE}$

...

$x_H = x_{FH} + x_{GH} = x_{HA}$

$x_{exit} = x_{Aexit}$

// Loopbound constraint

$x_A \leq 100$

// WCET Expression

$WCET = \max(x_A*3 + x_B*5 + x_C*7 + \ldots + x_H*2) = 3072$

Implicit path enumeration technique (IPET) [3] which is used in LLVMTA and Heptane

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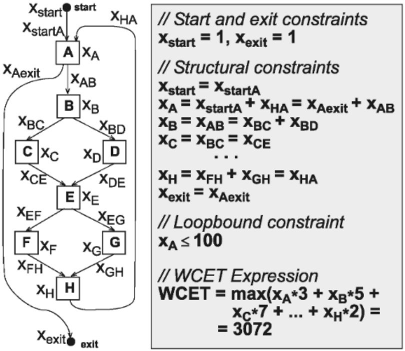

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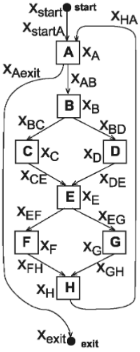
Static analysis

1. Obtain the Control Flow Graph (CFG) and find possible paths
2. Determine the possible execution times of blocks, accounting for the timing effects of microarchitectural features such as pipelining and caching
3. Combine info from 1 and 2 to obtain upper timing bounds [5]



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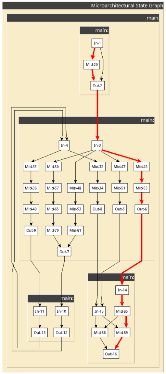
- Developed in Saarland University
- Aims for state-of-the-art analysis frameworks, in particular abstract execution graphs (AEG)
- Does not focus on the complexity of modeling real-world hardware architectures (like commercial tools, e.g. aiT)

Abstract execution graphs

- AEG may capture correlations between the timing contributions of different basic blocks, rather than computing a single bound for each basic block

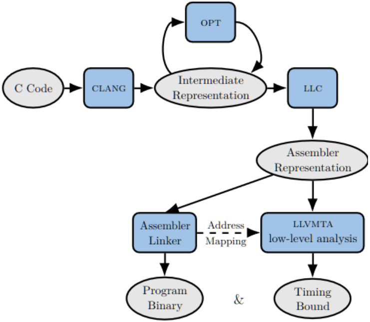
```c
int main() {
    int i = 0;
    while ( i < 50)
        ++i;
    return 0;
}
```

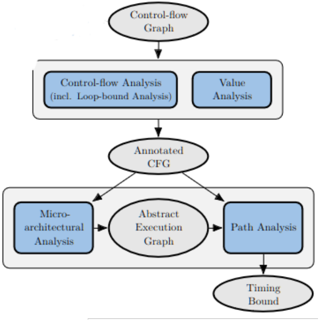


Multiple abstract microarchitectural states are created for the while loop in the main function allowing for higher analysis precision

LLVMTA architecture

- Analysis are implemented on the final assembler representation in the LLVM backend which is the representation closest to the machine level





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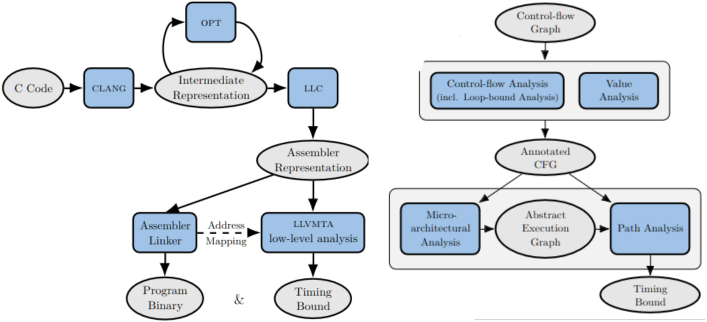

- Supports multiple ILP solvers: LPsolve, IBM CPLEX, and Gurobi Optimizer

Using LLVMTA

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  - ARM and RISC-V ISA
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  - Scratchpad memories, as well as caches with least-recently-used replacement policy and both write-through and write-back policy

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- Likewise the user has to provide annotations file for the external functions

An example

```c
int main() {
    int i = 0;
    while ( i < 50 ){
        i = printf(format: "%d\n", i);
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Both the loop bound and the external function printf are unknown

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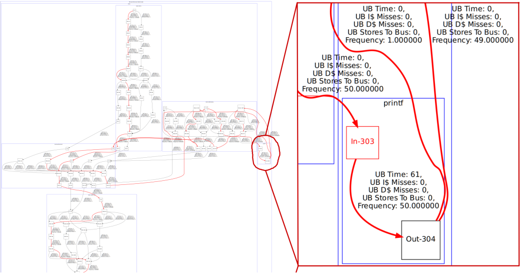
- The annotation files are given such that printf has 61 WCET and the loop has 50 iterations, the AEG becomes



LLVMTA limitations

- Since it operates on the machine-level IR rather than on the binary, results may be incorrect if
  - Another compiler is used for the binary
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- The tool is reasonable fast on the standard WCET benchmarks, but will likely not scale to real-world applications

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- Has limited hardware support

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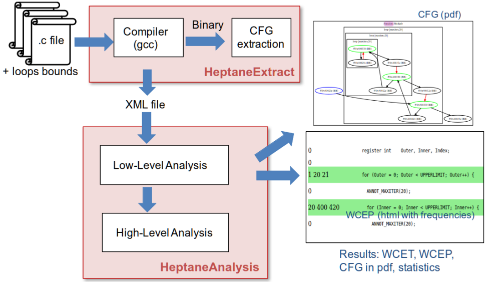
- Heptane is divided into two parts



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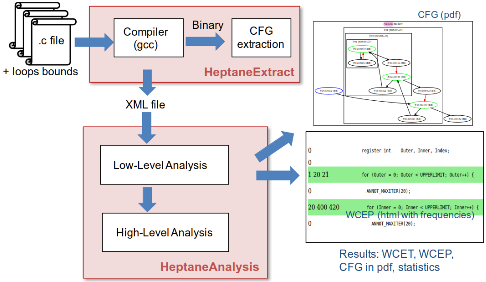

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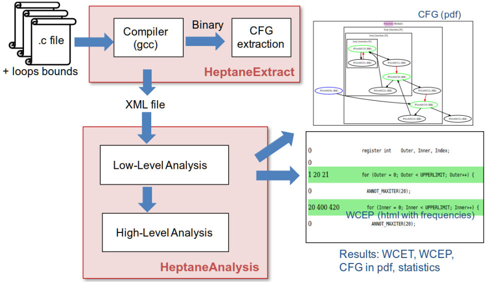

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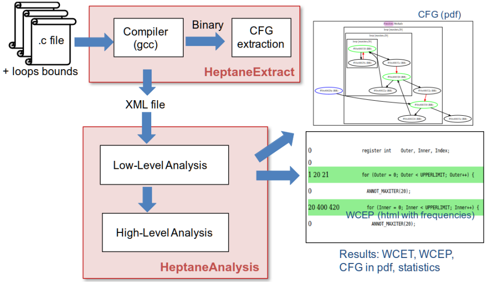

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- Heptane does not support handling external functions with annotations either

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simplewhile.c

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    return 0;
}
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        ANNOT_MAXITER(50);
        ++i;
    }
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Source codes for LLVMTA (left) and Heptane (right)

- For LLVMTA, even though the enable-optimizations flag is set to false, I had to remove -disable-O0-optnone flag for clang from inside the script. Otherwise the loop was removed in compilation and WCET was estimated as 52

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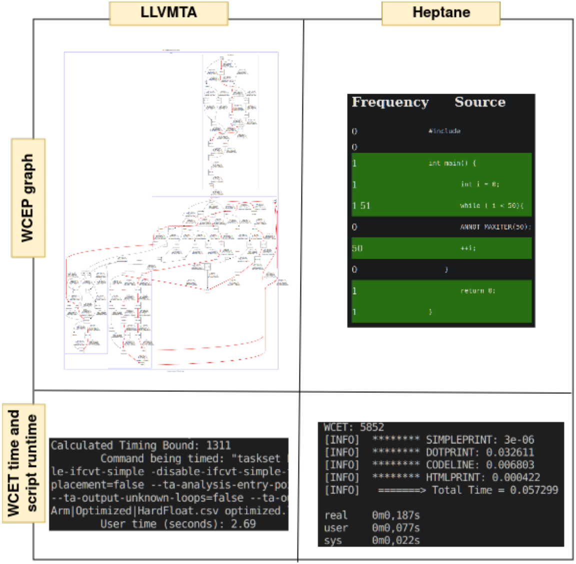
- After removing the flag LLVMTA fails to automatically determine the maximum loop bound and asks for annotations
- Heptane requires the annotations inside the source code meanwhile LLVMTA looks for it inside a seperate .csv file

Comparison of the results



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- The ISAs are both ARM but the hardwares are not configured equally so its difficult to comment onthe difference in WCET
- But considering the capabilites of LLVMTA and the logarithmic difference in runtimes, the best decision falls on what is prioritized, performance or accuracy
- I continued with LLVMTA because it was easier to be modified to analyze C++ files

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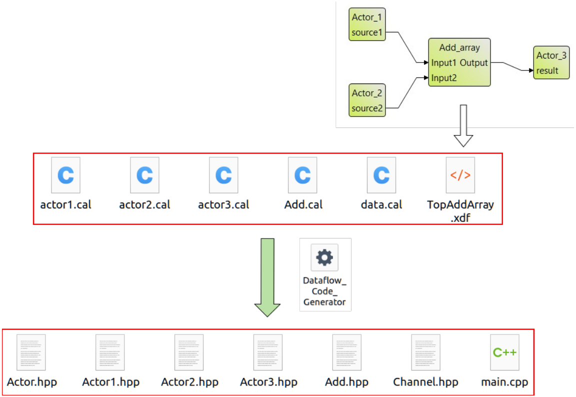
Dataflow Code Generator



- Converts dataflow networks specified in CAL and XDF to C++ code
- Serves as exploration tool for different optimization and mapping strategies

Running LLVMTA for C++

```
208       - clang "${clangopts[@]}" -emit-llvm "$TESTCASE_DIR"/*.c
      208 + clang ${clangopts[@]} -emit-llvm "$TESTCASE_DIR"/*.c*
```

```
3 testcases/dataflowActorsUtils/ClangSpecialOptions.txt
...   @@ -0,0 +1,3 @@
1   + -stdlib=libstdc++
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Two simple tricks

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- So not the most elegant solution, and might be the reason for the bugs which will be mentioned

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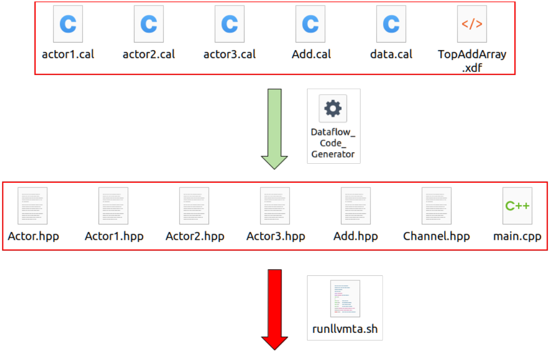
Two simple tricks

- So not the most elegant solution, and might be the reason for the bugs which will be mentioned
- Correct cross compiler libraries are needed for sure

Unsuccessful attempt




```
llvmta: /workspaces/llvmta/lib/LLVMPasses/StaticAddressProvider.cpp:173: bool TimingAnalysisPass::StaticAdd
 Assertion `0 && "We have unhandled pseudo instructions"' failed.
PLEASE submit a bug report to https://github.com/llvm/llvm-project/issues/ and include the crash backtrace.
```

The stack trace points to schedule function in main, which is the actual function we are interested in WCET analysis of

Modifying actor files

```
    void sendData$(void) {
        unsigned char Out;
        Out = SRC1[i];
        i = i+1;
        source1->write(t: Out);
    }
public:
    Actor1(std::string _n, Data_Channel<char>* _source1) {
        actor$name = _n;
        source1 = _source1;
    };
    void schedule(void) {
#ifdef PRINT_FIRINGS
        unsigned firings = 0;
#endif
        for(;;) {
            if (true) {
```

```
    void sendData$(void) {
        unsigned char Out;
        Out = SRC1[i];
        i = i+1;
        source1->write(t: Out);
    }
    int main(int argc, char* argv[]) {
#ifdef PRINT_FIRINGS
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```
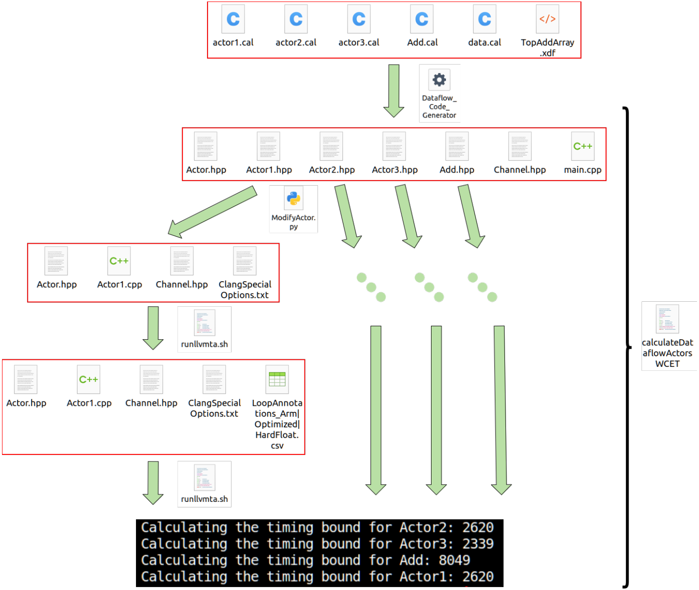

Modify all actor files so that we can do LLVMTA run on schedule functions seperately

Final structure




```
Calculating the timing bound for Actor2: 2620
Calculating the timing bound for Actor3: 2339
Calculating the timing bound for Add: 8049
Calculating the timing bound for Actor1: 2620
```

Final remarks

- This workflow throws errors sometimes with more comples networks, at the loop bounds extraction phace of LLVM

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- This workflow throws errors sometimes with more comples networks, at the loop bounds extraction phace of LLVM
- A better solution is to create C code from CAL sources and run the WCET tools

References

[1] P. Puschner, R. Kirner, and B. Huber. *Worst-Case Execution-Time Analysis – WCET Analysis*. https://ti.tuwien.ac.at/cps/teaching/courses/real-time-systems/slides/rts06_wcet_analysis-1.pdf. [Online; accessed 09-April-2024].

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