A framework to experiment optimizations for real-time and embedded software

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Current Section

Real-time embedded systems

- Embedded systems constraints
  - Limited memory ⇒ limited code size
  - Possible need for autonomy and/or inability to use efficient but voluminous cooling equipments ⇒ low energy consumption
- Real-time applications
  - Hard or soft timing deadlines

⇒ Various optimizations must be applied in order to meet requirements!

- ANR granted MORE Project: **M**ulti-criteria **O**ptimizations for **R**eal-time **E**mbedded Systems

Code transformations

- Optimizations through code transformations to meet system requirements
  - Code size requirements
    - Compiler optimizations to reduce the number of instructions
    - Code compression
  - Energy requirements
    - Compiler transformations to reduce the number of memory accesses
    - Data placement strategies to optimize the use of various memories of the hardware
  - Worst-case execution time (WCET) requirements
    - Different kinds of code transformations, like loop unrolling or function inlining, aiming to remove flow control instructions

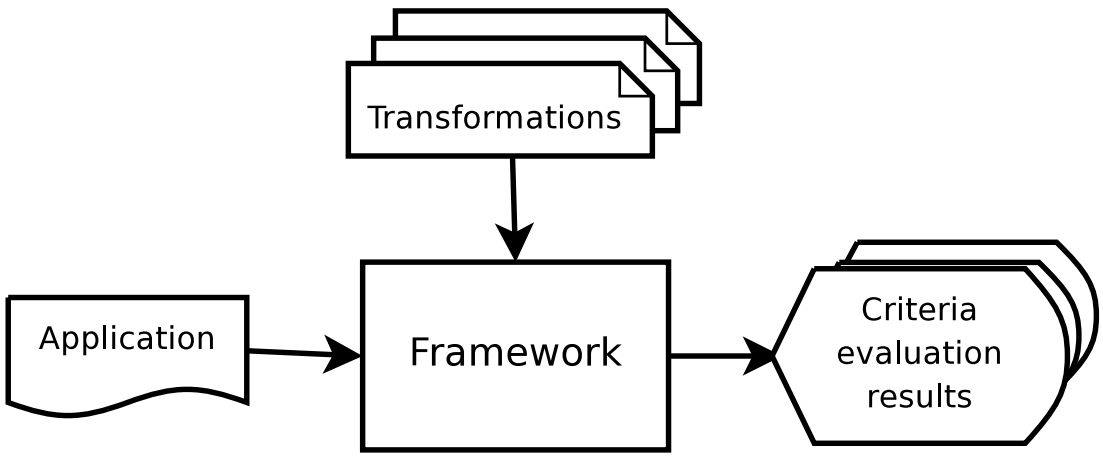
Side effects of transformations

- A sole transformation can have effects on several criteria
  - Code compression targets code size but can impact energy consumption, average and worst case execution times
  - Data placement strategies target energy consumption but can also impact average and worst case execution times
  - WCET related code transformations can also impact code size and energy consumption

$\Rightarrow$ To achieve a multi-criteria optimization, we must carefully analyze the effects of multiple transformations

A common framework

- A **common** framework for all transformations and evaluations is the key



  - Allows rapid and easy experimentation
  - Reduces time to market

Current Section

OTAWA: Open Tool for Adaptive WCET Analysis

- OTAWA: A framework dedicated to worst-case execution time analysis, including
  - tools to load and decode binary codes (PowerPC, ARM7, TriCore, Star12X)
  - tools to build a representation of the code (CFG: Control Flow Graph)
  - code processors that allow easy implementation of static code analyses
  - annotation facilities that allow hooking attributes (e.g. results of analyses/transformations) to any code object
  - cycle level simulator built on top of SystemC
    - supports superscalar pipelines, in-order and out-of-order execution, branch prediction, instruction and data caches, scratchpad memories, user-specified memory architecture...

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Energy-aware memory mapping

- Take advantage of different behaviors of the heterogeneous memories with respect to energy
  - e.g. main memory, cache memory, scratchpad memory (SPM)
  - Place the most accessed data in the less energy-hungry memories
    - SPM is targeted for its efficiency in energy consumption
- 3 strategies of static date placement:
  - *SPM_firstUsed*, *SPM_smallSizeFirst*, *SPM_highFrequency*
  - Static data placement avoids interacting with code compression and improves timing predictability
- Implementation of the transformation
  - A pre-run is performed to trace accesses to each piece of data
    - Added probes to `OTAWA` simulator
  - The trace is used to perform data mapping prior to actual run
    - New memory mapping is emulated in `OTAWA` by working on data accesses

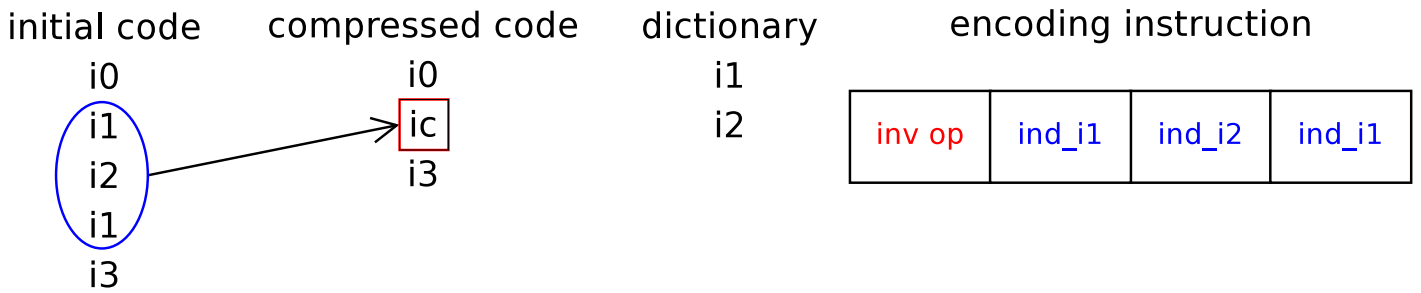
Principles of code compression

- The code size is reduced by compacting the code into a non executable format
- A decompression step is needed at runtime to retrieve the initial code

- Dictionary based compression is selected for the MORE project
  - Suffers from lower compression rate but allows simple and very fast decompression
- In-pipeline decompression is selected for the MORE project
  - The decompression engine is between fetch and decode stages
  - The cache contains compressed code and becomes virtually larger which results in fewer cache misses and fewer memory accesses

    $\Rightarrow$ Can improve performance and decrease energy consumption

Dictionary based code compression



- Build the dictionary with instructions from the initial code
- Compact these instructions into an encoding instruction containing corresponding dictionary indexes
- How to choose the instructions to include in the dictionary?
  - Most repeated instructions to improve compression rate
  - Most executed instructions to reduce instruction cache misses
  - Our solution: a mixture of both
    - P% of the dictionary is filled with the most executed and the rest is filled with the most repeated instructions
- Implementation of the transformation
  - Compressed instructions are annotated so in `OTAWA`
  - Simulator is modified to simulate the pseudo-compressed code

WCET related transformations

- The transformations considered to improve the WCET consist in linearizing the code (e.g. function inlining, loop unrolling)
  - Removal of flow control instructions improves predictability of processor states
- Implementation of transformations
  - Could be implemented by modifying the CFG in `OTAWA`
  - Most compilers already support this kind of transformations
  - A plugin is developed to control loop unrolling and function inlining through the `GCC Interactive Compilation Interface`

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Energy consumption evaluation

- A simple model of consumption based on the number and the cost of each kind of access to different memory types
- The cost of a read/write operation of each memory component is calculated through the `CACTI` tool
- Added probes to `OTAWA` simulator to obtain read/write access counts for each memory component (caches, DRAM, SPMs and dictionary)
- Finally, energy consumption is calculated by multiplying access costs by access counts

WCET analysis

- WCET analysis tool uses several components of `OTAWA`
  - instruction and data cache analyzers based on abstract interpretation techniques
  - a timing analyzer that evaluates WCET of basic blocks taking into account the target architecture and cache analysis
  - a WCET computation tool that builds an integer linear program according to IPET method which is then solved by the `lp_solve` tool
- Effects of code compression are taken into account by
  - considering the address of the instruction in the compressed code in instruction cache analysis
  - considering the effect of the decompression engine in basic block WCET evaluation
- The data cache analyzer interfaces with the data placement tool to get the information about the memory in which every piece of data is stored

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Test programs and hardware platform

- Experimented with 4 test programs
  - `adpcm`: adaptive pulse code modulation algorithm
  - `compress`: data compression program
  - `helico`: toy helicopter control program
  - `segmentation`: image segmentation algorithm
- Hardware platform
  - 2-way superscalar in-order processor
  - 1KB 2-way associative instruction and data caches - a small cache is chosen to get realistic results with the small test programs
  - To test data placement strategies
    - 512B 2-way associative data cache and 512B SPM

Impact of a data placement strategy

- Effects of *SPM_highFrequency* strategy

Benchmark	**Impact on energy**	**Impact on WCET**
`adpcm`	−13.3%	−23.8%
`compress`	−65.9%	−18.5%
`helico`	−7.7%	−5.9%
`segmentation`	−10.7%	N/A
average	−24.4%	−16.1

  - Traditional caches are much more energy hungry than SPMs and they are also very unpredictable which causes an over-estimation of WCET

⇒ Coupling a cache and an SPM with an adequate strategy can yield to important energy savings and improve WCET estimation compared to a single large cache

Global impact of code compression

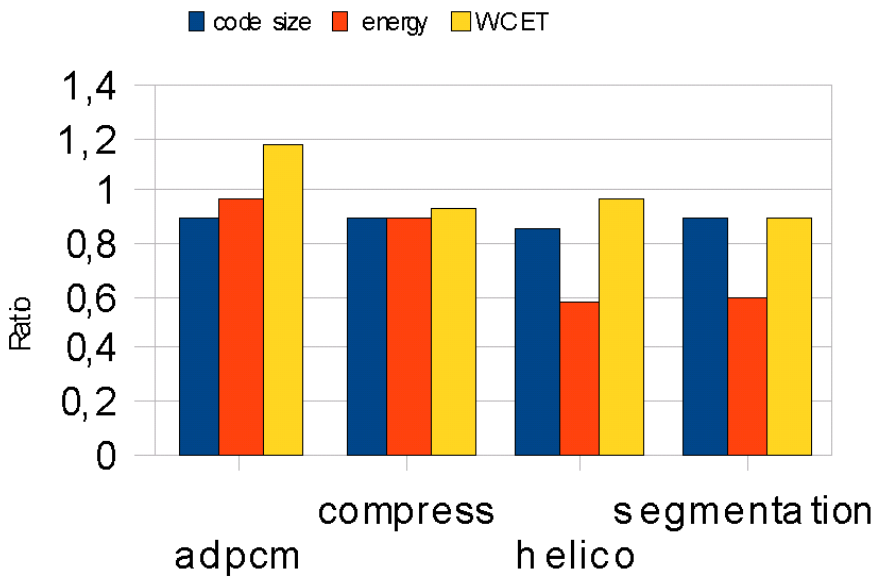
- P: the percentage of the dictionary filled with the most executed instructions
  - The lower the value of P the better the compression rate
  - The higher the value of P the better the execution time and the energy consumption reduction except where code compression creates conflicts misses
    - Since code placement with respect to the cache is modified by compression, instruction cache misses can increase in pathological cases
  - There is no direct correlation between P and the impact on the WCET
    - It can even be degraded!

$\Rightarrow$ A careful trade-off is necessary to meet system requirements

- Beware of pathological cases!

Effects of code compression

- Effects of code compression with a different value of P for each benchmark that leads to a good trade-off



⇒ Code compression can improve the WCET and energy consumption while reducing the code size but fine tuning of each application is required

Function inlining

- Function inlining replaces calls to functions with their bodies
  - Code becomes more linear
    - $\Rightarrow$ over-estimation of the WCET gets smaller
  - Performance tends to increase because
    - call/return instructions as well as prologue/epilogue code of functions are removed
    - function body can be optimized for the context of the caller
  - Has negative effects too
    - code size is increased
    - temporal locality of accesses to the instruction cache is decreased

Effects of function inlining

Benchmark	Impact on WCET	Impact on code size	Impact on energy
`adpcm`	−1.5%	+45.5%	−5.2%
`compress`	−6.5%	+44.5%	−0.9%
`helico`	−7.4%	+95.9%	−73.9%
average	−5.1%	+62.0%	−26.6%

- Gain on WCET is moderate but a larger cache would help in benefiting more from inlining
- Inlining significantly expands code size
  - Strategies to trade-off between the code size and the WCET should be set up
- Inlining decreases the number of instruction cache accesses but can also increase the number of misses

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Conclusion

- Embedded systems are subject to various constraints like code size, power requirements, execution time, etc.
- Code transformations can be necessary to meet these constraints, e.g.
  - code compression can improve code size
  - data placement strategies can improve energy consumption
  - limiting jump instructions can improve WCET estimation
- Experimenting several possible transformations is a costly and time consuming process

Conclusion and future work

- We have introduced a framework with the goal of hosting various transformations and measurements or analysis tools to facilitate the optimization process
- Using the framework, it is possible to
  - select the transformations that improve a target criterion
  - evaluate their effects on other important criteria
- The usability of the framework is shown with experimental results which suggest that
  - it is necessary to set up appropriate strategies to combine several transformations
- As a second part of the MORE project, we are developing an engine for iterative optimizations
  - controls the application of various transformations
  - tries to determine the best combination
  - takes into account system constraints

END

THANK YOU !!!

Questions?