WCET-Aware C Compiler: WCC

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(slides are based on Prof. Heiko Falk)
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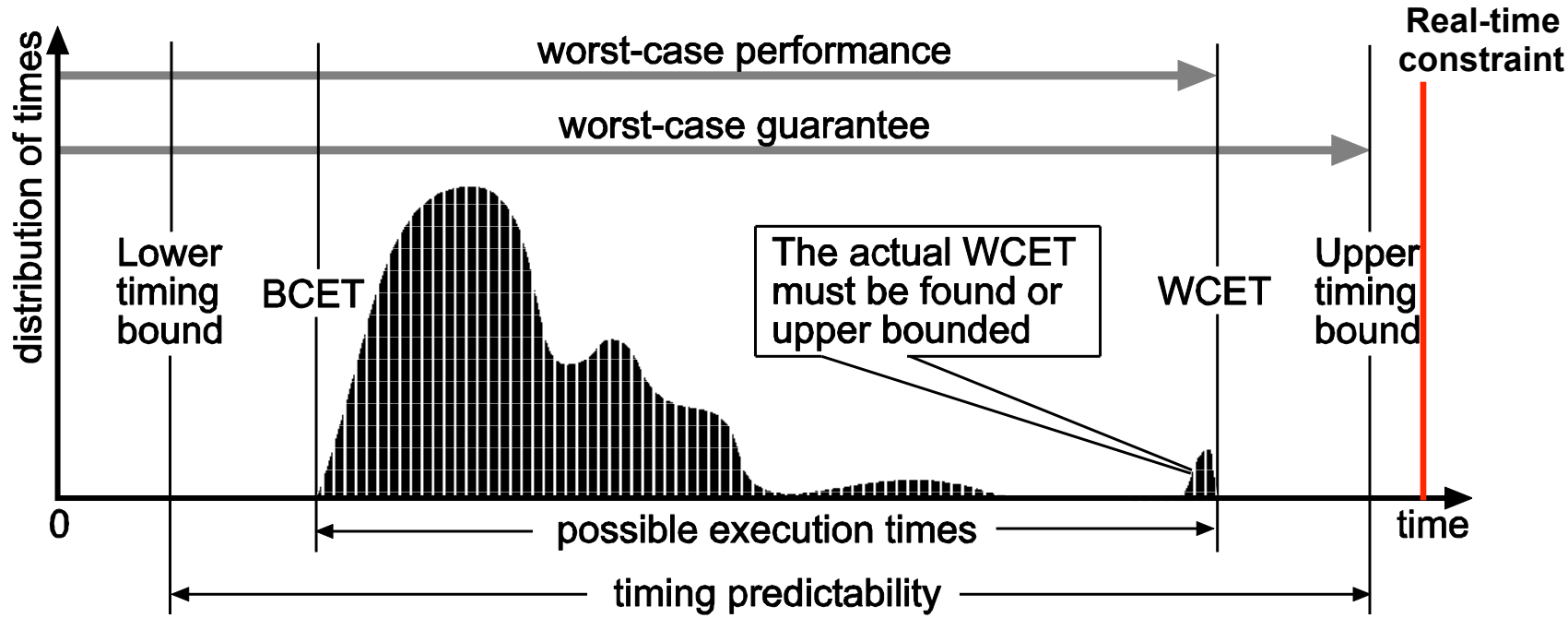
Worst-Case Execution Times *(WCET)*



Requirements

–*Safeness:* WCET ≤ $WCET_{EST}$!

–*Tightness:* $WCET_{EST}$ – WECT ⇝ minimal

WCET in general not computable

[Borrowed from Reinhard Wilhelm]

Design of Real-Time Systems

Current Industrial Practice *(Automotive, Avionics)*

1. Specification using graphical / high-level tools
2. Automatic generation of ANSI-C code
3. Translation into executable machine code for a given processor architecture
4. Repeated executions / simulations of generated machine code, usage of “representative“ input data
5. Time measurements provide *“observed execution times“*
6. Addition of safety margin (e.g. 20%) to greatest observed execution time: *„observed Worst-Case Execution Time“*
7. Observed WCET ≤ Real-time constraint? No: goto 1

Problems of this Design Flow

Safety

–No guarantee that observed WCET (even only approximately) matches the actual WCET

☞No guarantee that a real-time system *always* terminates in time

Design Time

–How many iterations are required until step 7 successful?

☞Depends on in how far steps 2-3 lead to the effective acceleration of the generated code in the worst case

☞*Try & Error* until step 7 successful

Current State of the Art in Compiler Construction

Objective Function of Compiler Optimizations

–Usually reduction of *Average-Case Execution Times (ACET)*: Accelerate a “typical” execution of a program using “typical” input data

☞No statements about WCETs possible

Optimization Strategy

–Naive: Current compilers lack precise ACET timing model

–Application of an optimization if “promising”

☞ACET-related effects of optimizations unknown to the compiler

☞ACET optimizations potentially increase WCETs – Compilers often invoked without any optimizations for real-time systems

Motivation

Design of a Compiler that

–considers $WCET_{EST}$ instead of average-case runtimes,

–allows formal guarantees on worst-case properties, instead of relying on observed execution times,

–applies fully automated optimizations to minimize $WCET_{EST}$.

Approach

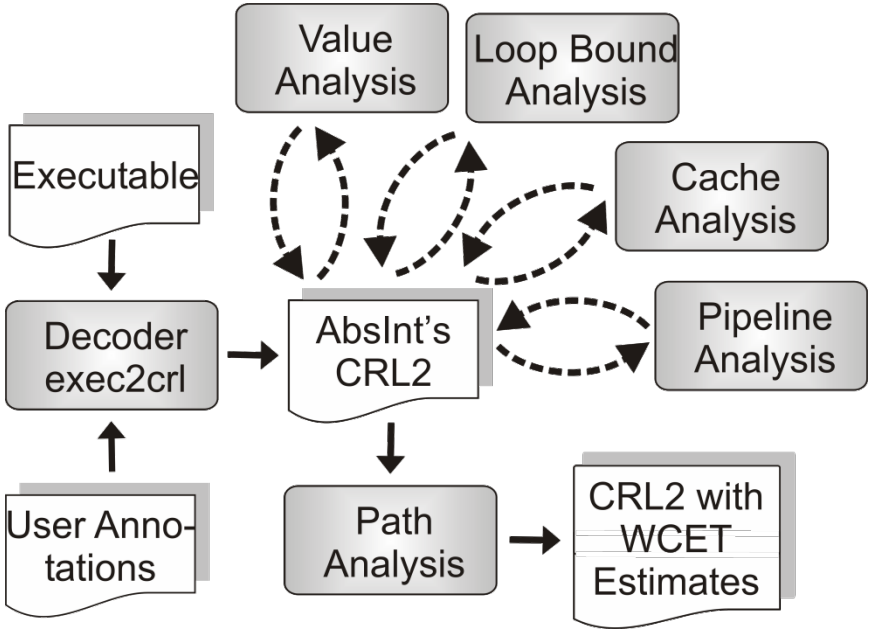
–Integration of a $WCET_{EST}$ timing model into compiler by coupling compiler back-end with static WCET analyzer.

–Exploitation of $WCET_{EST}$ timing model by optimizations explicitly aiming at $WCET_{EST}$ minimization.

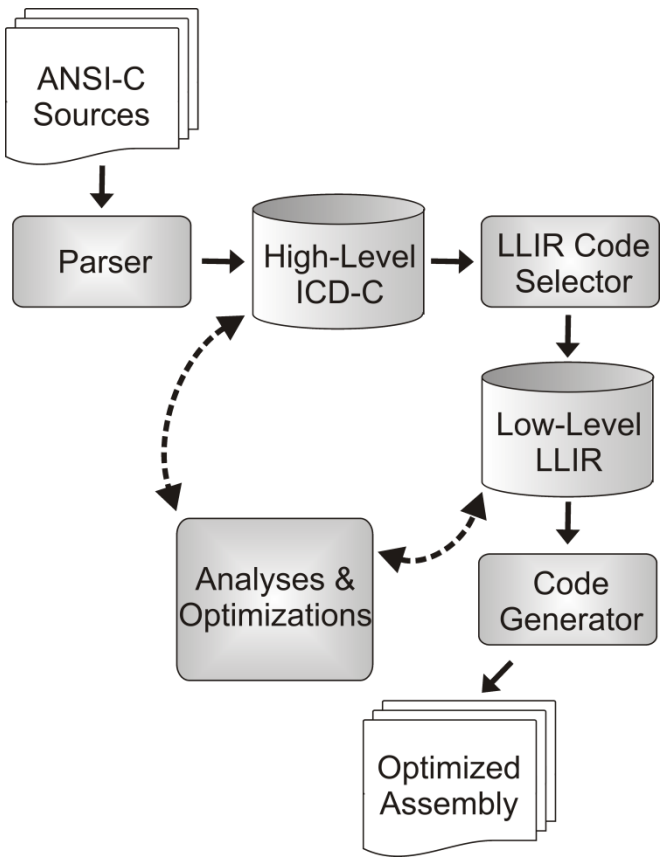
Adopting aiT in Compilation

–**Solution:** The user of aiT must mandatorily provide information about e.g. minimal and maximal iteration bounds of loops and recursion depths.

–**Annotation file:** Contains such user-provided annotations *("Flow Facts")* and is – besides the program *P* to be analyzed – another external input to aiT.



Integration of WCET into WCC Compiler (1)



–Supported processors: Infineon TriCore TC1796 and TC1797; ARM7

–Re-implementation of a WCET timing model in compiler makes no sense

–Instead: Tight integration of aiT

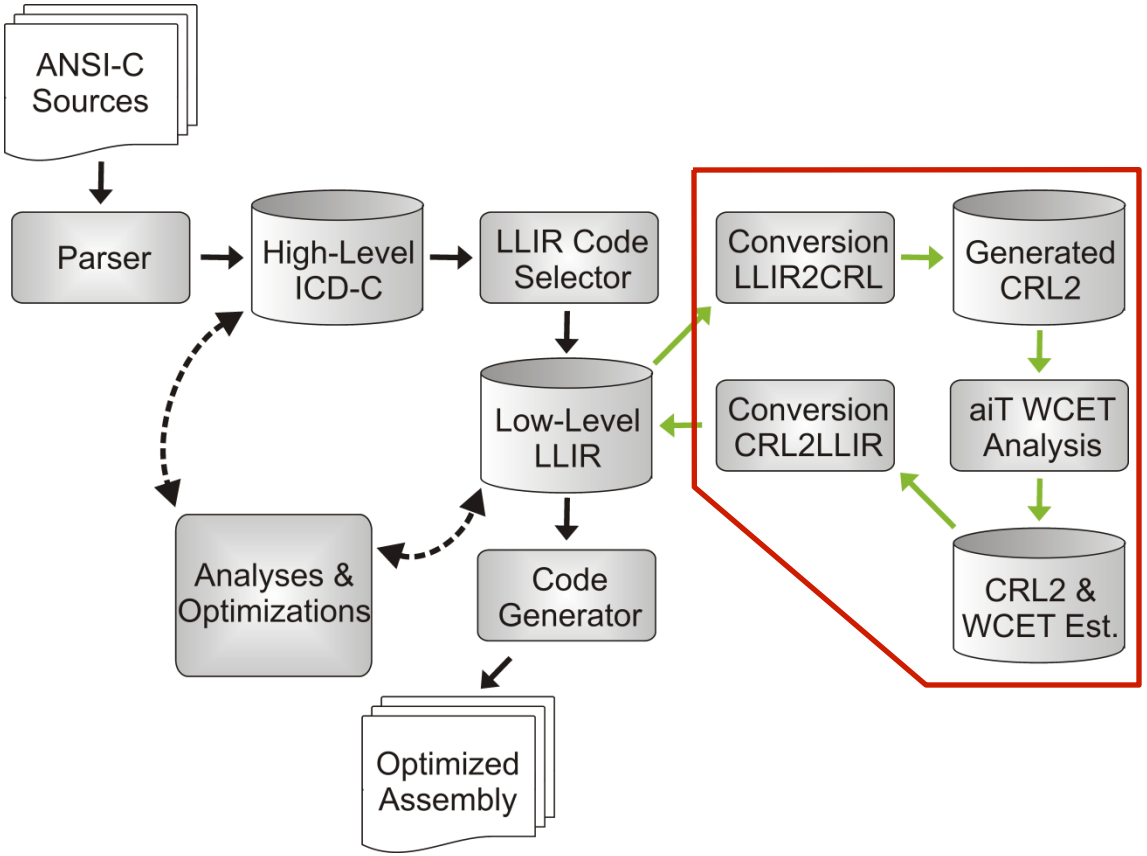
–Coupling inside processor-specific compiler back-end *(LLIR)*

–Seamless exchange of information via translation LLIR ↔ CRL2

–Transparent invocation of aiT inside the compiler

–Import of WCET-related data into compiler back-end

Integration of WCET into WCC Compiler (2)



Relevant WCET data:

–$WCET_{EST}$ of entire program, function of basic block

–Worst-Case execution frequency per function, basic block or CFG edge

–Potential register contents

–Cache hits / misses per basic block

[http://ls12-www.cs.tu-dortmund.de/research/activities/wcc]

Memory Hierarchies and Execution Times

Memories and Execution Times

–Overall system performance largely dominated by memory subsystem

–Large speed gap between slow memories and fast processors

–Execution time of software depends on characteristics

- ☞ of underlying memory hierarchy and
- ☞ of memory accesses performed by a program

☞WCET estimates also heavily depend on memories!

Flow Facts (1)

WCET Analysis

–Estimates the longest possible execution path

–Such paths can contain cycles stemming from loops and/or recursions

☞How many times are such cycles iterated in the worst case?

☞Traversals of cycles have to be upper-bounded for WCET analysis!

Flow Facts...

–... are (user-provided) meta-information containing such upper bounds

–... have to be supported by a WCET-aware compiler

Flow Facts (2)

aiT's Flow Fact Support

–Via separate annotation file

–Contains loop bounds and recursion depths at machine code level, i.e. based on physical memory addresses

☞Extremely low-level, tedious to generate Flow Facts

☞Cumbersome since Flow Facts must be (manually) updated if a program's memory layout changes

WCC's Flow Fact Support

–High-level, directly within ANSI-C source codes

–No relation to machine code level required for programmer

–Automatic Flow Fact update during code transformations

Annotation of Loop Bounds

Simple Loops with Constant Bounds

```
_Pragma( "loopbound min 100 max 100" )
for ( i = 1; i <= 100; i++ )
  Array[ i ] = i * fact * KNOWN_VALUE;
```

A Data-dependent Loop

–E.g. if loop depends on a function's parameter **`maxIter`** whose possible min/max values are known:

```
_Pragma( "loopbound min 50 max 100" )
for ( i = 1; i <= maxIter; i++ )
  Array[ i ] = i * fact * KNOWN_VALUE;
```

Annotation of Flow Restrictions

A Triangular Loop

```
  _Pragma( "marker outer" )
  Statement A;

  for ( i = 0; i < 10; i++ )
    for ( j = i; j < 10; j++ )
      _Pragma( "marker inner" )
      Statement B;

  _Pragma( "flowrestriction 1*inner <=
55*outer" );
```

To read as follows

–The execution frequency of **B** is at most 55 times that of **A**

Automatic Loop Bound Analysis

Disadvantages of Manual Flow Fact Annotation

–Time-consuming procedure for developer

–“Stupid” and error-prone work

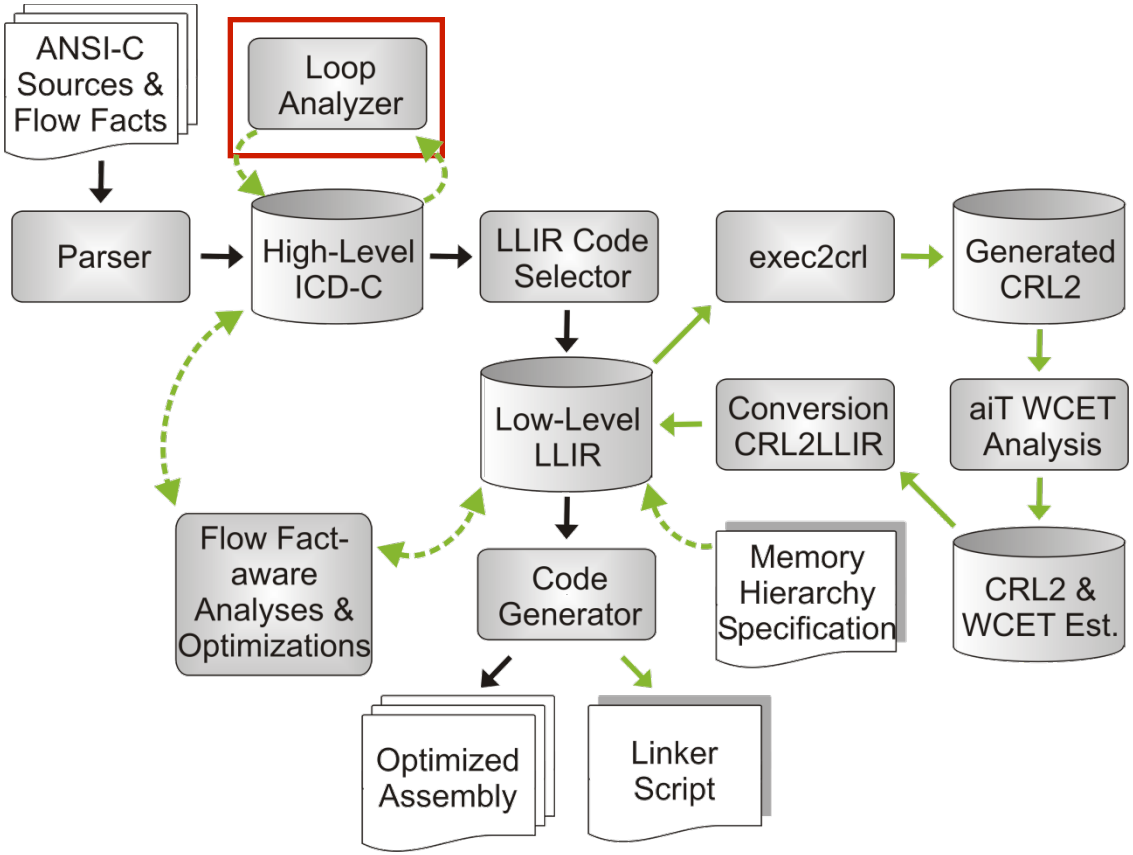
–Risk of wrong annotations and thus unsafe WCET estimates

WCC’s Automated Loop Analyzer

–Operates on high-level IR ICD-C, i.e. on ANSI-C code

–Automatically extracts loop bound Flow Facts required for WCET analysis for broad classes of loops

WCC's Loop Analyzer



- 99% of 707 loops analyzable
- Exact loop iteration counts for 96% of the loops
- Analysis times between few CPU seconds and max. 4 minutes
- Automatic generation of loop bound Flow Facts

*[**P. Lokuciejewski,** A Fast and Precise Static Loop Analysis..., CGO, 2009]*

Challenges during $WCET_{EST}$ Minimization

The *Worst-Case Execution Path (WCEP)*

–WCET of a program = Length of the program's longest execution path (WCEP)

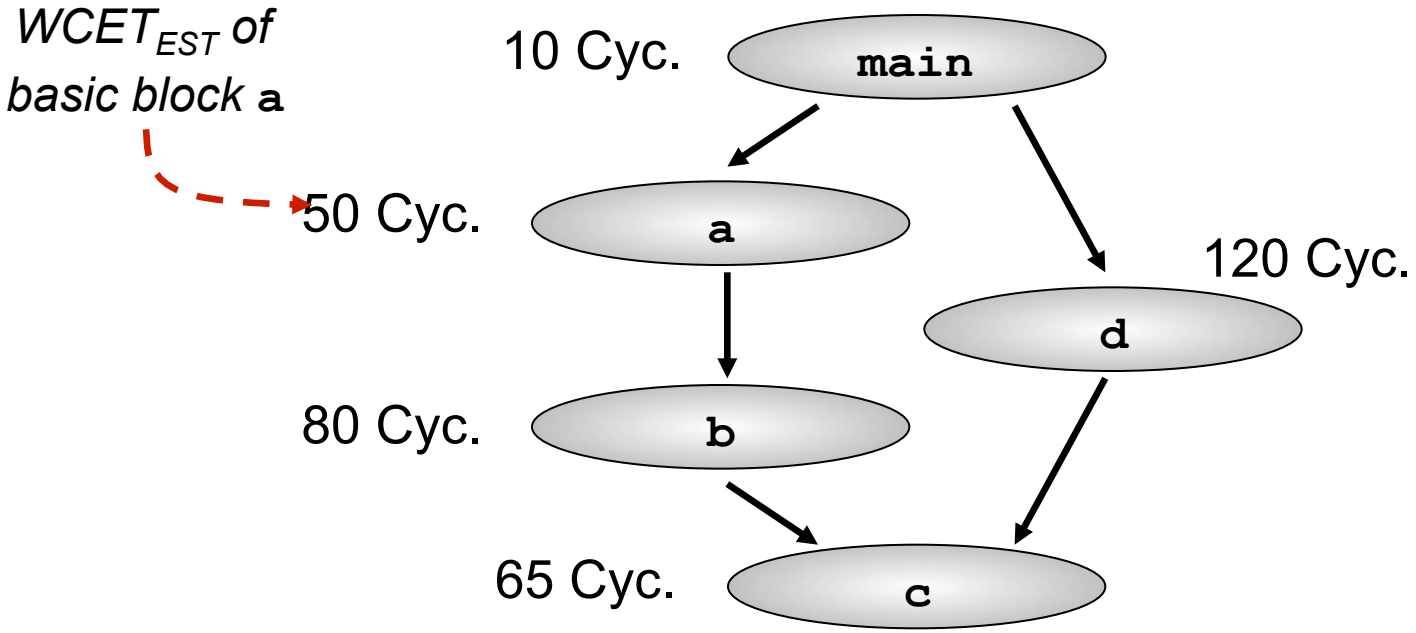
–$WCET_{EST}$ Minimization: Optimization of only those parts of a program lying on the WCEP

–Code optimization apart the WCEP will not reduce $WCET_{EST}$

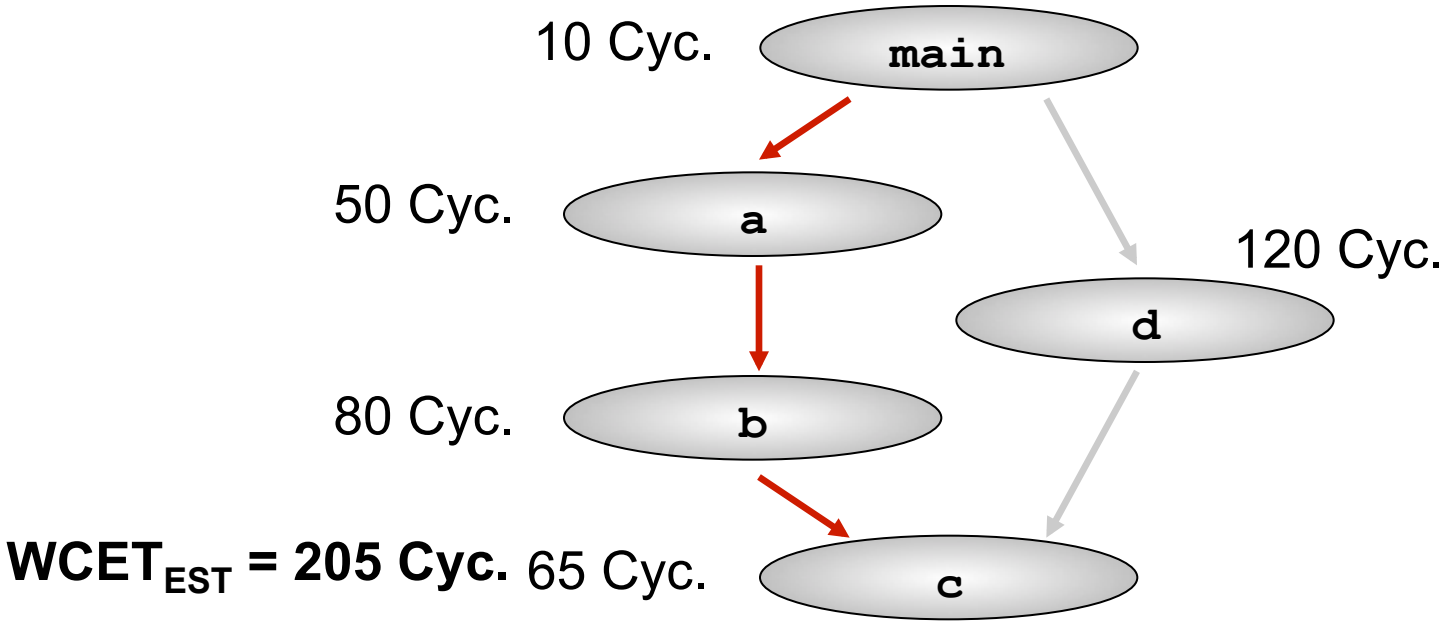
☞Optimizations minimizing $WCET_{EST}$ require detailed knowledge of the WCEP...

☞***WCET analyzer aiT provides such detailed information by means of execution frequencies of CFG edges, but...***

Instability of the WCEP (1)

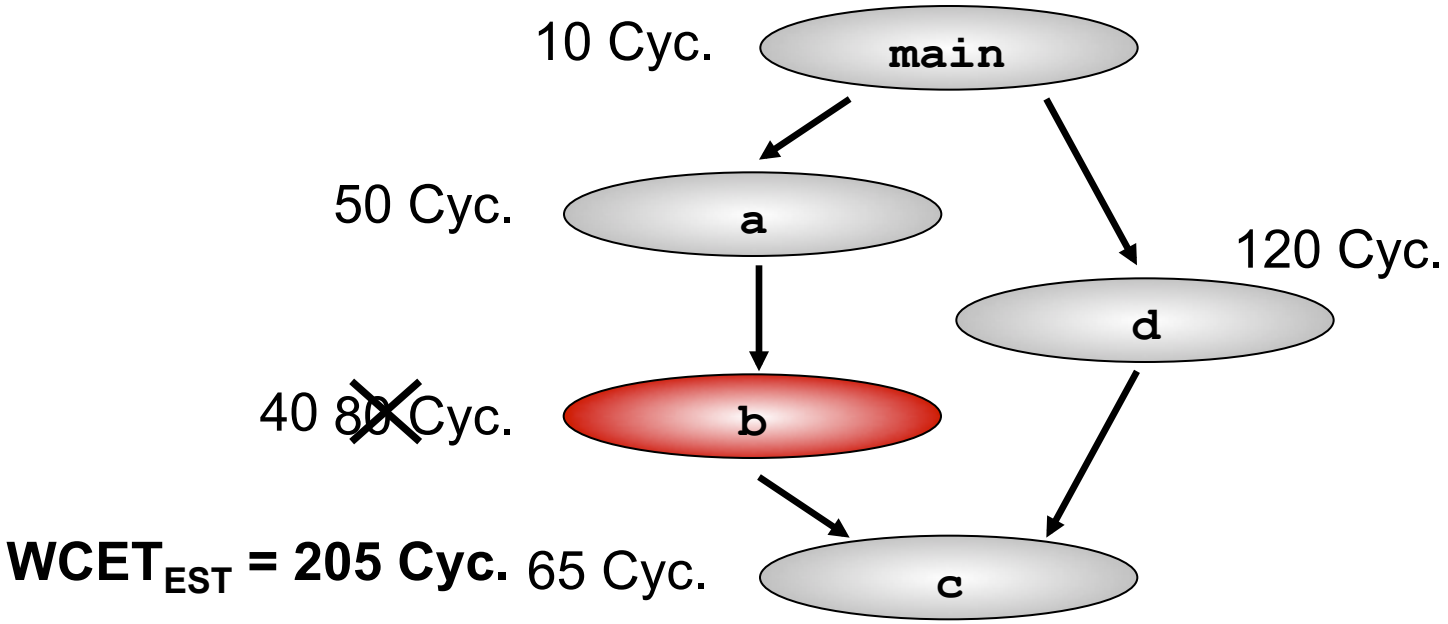


Instability of the WCEP (2)



- Initial WCEP: **`main`**, **`a`**, **`b`**, **`c`**
- Length of WCEP = $WCET_{EST}$: 205
- In the following: optimization of **`b`**

Instability of the WCEP (3)



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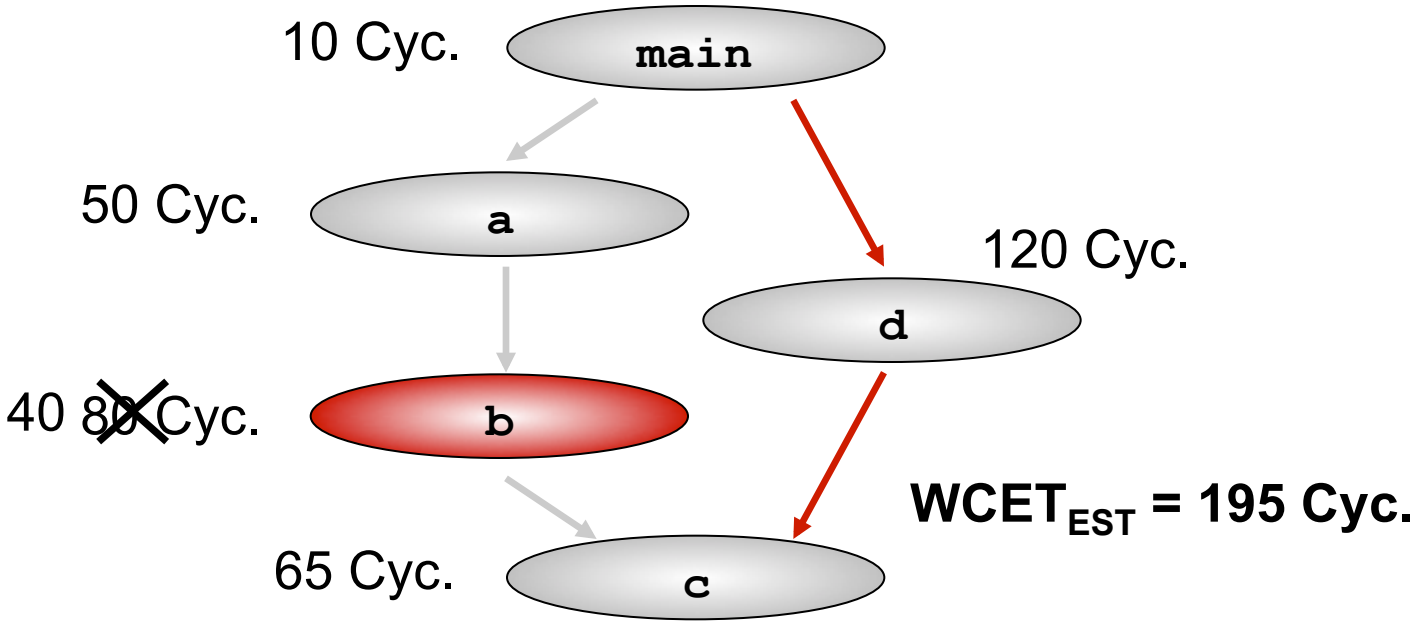
- In the following: optimization of **`b`**

Instability of the WCEP (4)



- Novel WCEP: **`main`**, **`d`**, **`c`**
- Novel WCET$_{EST}$: 195

☞ ***WCEP has changed due to an optimization!***

Challenges during $WCET_{EST}$ Minimization

The Worst-Case Execution Path (WCEP)

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–$WCET_{EST}$ Minimization: Optimization of only those parts of a program lying on the WCEP

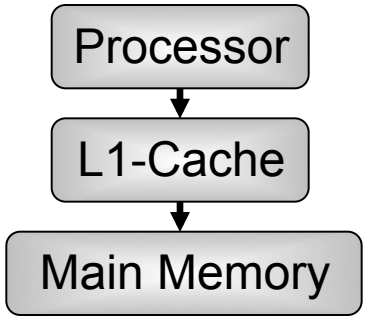
–Code optimization apart the WCEP will not reduce $WCET_{EST}$

☞Optimizations minimizing $WCET_{EST}$ require detailed knowledge of the WCEP...

☞***... and of its changes in the course of an optimization.***

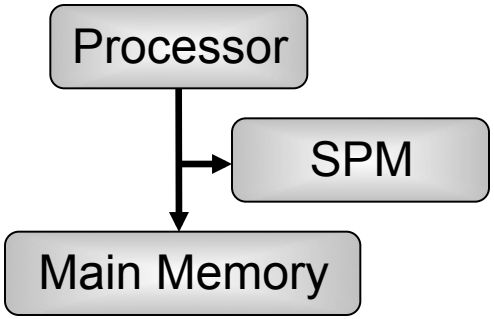
Caches vs. Scratchpad Memories *(SPM)*

Caches:



- Hardware-controlled
- Cache contents difficult to predict statically
- Latencies of memory accesses highly variable
- $WCET_{EST}$ often imprecise

Scratchpads:



- No autonomous hardware
- SPM seamlessly integrated in processor's address space
- Latencies of memory accesses constant
- $WCET_{EST}$ extremely precise

ILP for WCET-aware SPM Allocation of Code

- **Goal**
  - Determine set of basic blocks to be allocated to the SPM
  - ...such that selected basic blocks lead to overall minimization of $WCET_{EST}$
  - ...under consideration of switching WCEPs.

- **Approach**
  - Integer-linear programming *(ILP)*
  - ☞ Optimality of results: no need for backtracking techniques

  - In the following: uppercase = constants, lowercase = variables

Decision Variables & Costs

- **Binary decision variables per basic block (BB):**

$$x_i = \begin{cases} 1 & \text{if basic block } b_i \text{ is assigned to } mem_{spm} \\ 0 & \text{if basic block } b_i \text{ is assigned to } mem_{main} \end{cases}$$

- **Costs of basic block b_i:**

$$c_i = C^i_{main} * (1 - x_i) + C^i_{spm} * x_i$$

c_i models the $WCET_{EST}$ of b_i if it is allocated to main memory or SPM, respectively

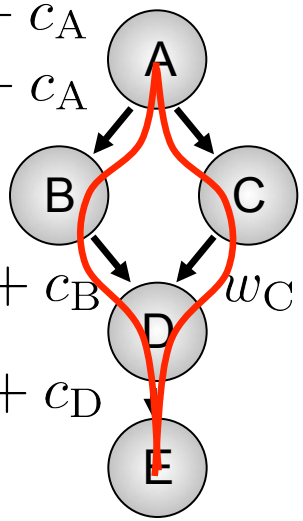
Intraprocedural Control Flow

- **Modeling of a function's control flow:**

Acyclic sub-graphs:

$w_A \geq w_B + c_A$

$w_A \geq w_C + c_A$



$w_B \geq w_D + c_B$

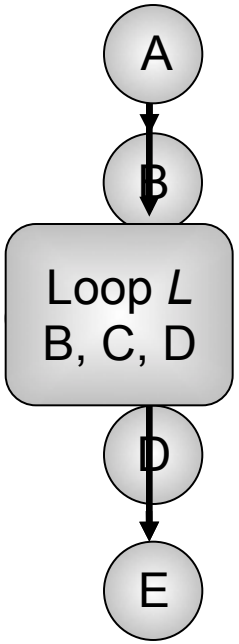
$w_C \geq w_D + c_C$

$w_D \geq w_E + c_D$

$w_E = c_E$

w_A = WCET of *any* path starting at A

(Reducible) Loops:



- Treat body of inner-most loop *L* like acyclic sub-graph
- Fold loop *L*
- Costs of *L*:

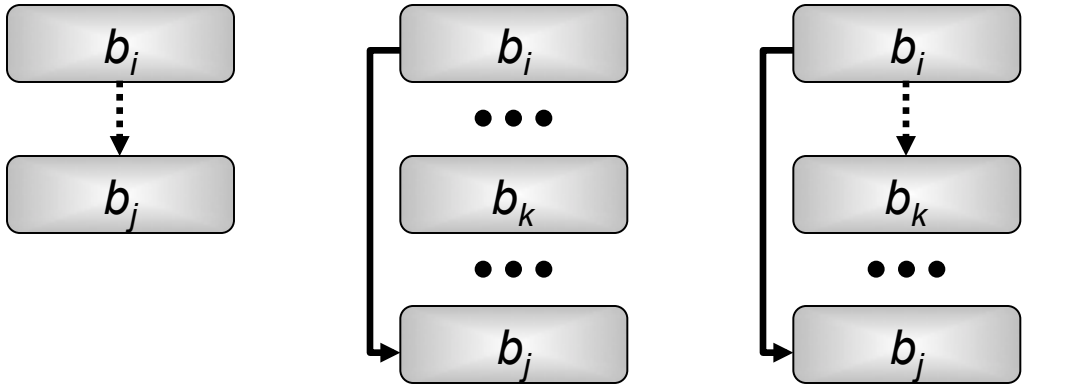
  $c_L = w_B * C^L_{max}$
- Continue with next innermost loop

*[**V. Suhendra et al.**, WCET Centric Data Allocation to Scratchpad Memory, RTSS 2005]*

Cross-Memory Jumps

- **Allocation of consecutive BBs:**
  - Allocation of consecutive BBs in the CFG to different memories requires adaption/insertion of dedicated jumping code
  - Cross-memory jumps are costly
  - Jumping code: *variable* overhead in terms of $WCET_{EST}$ and code size, depending on decision variables

- **Jump scenarios:**



a) Implicit ***b) Unconditional*** ***c) Conditional***

Scratchpad Capacity

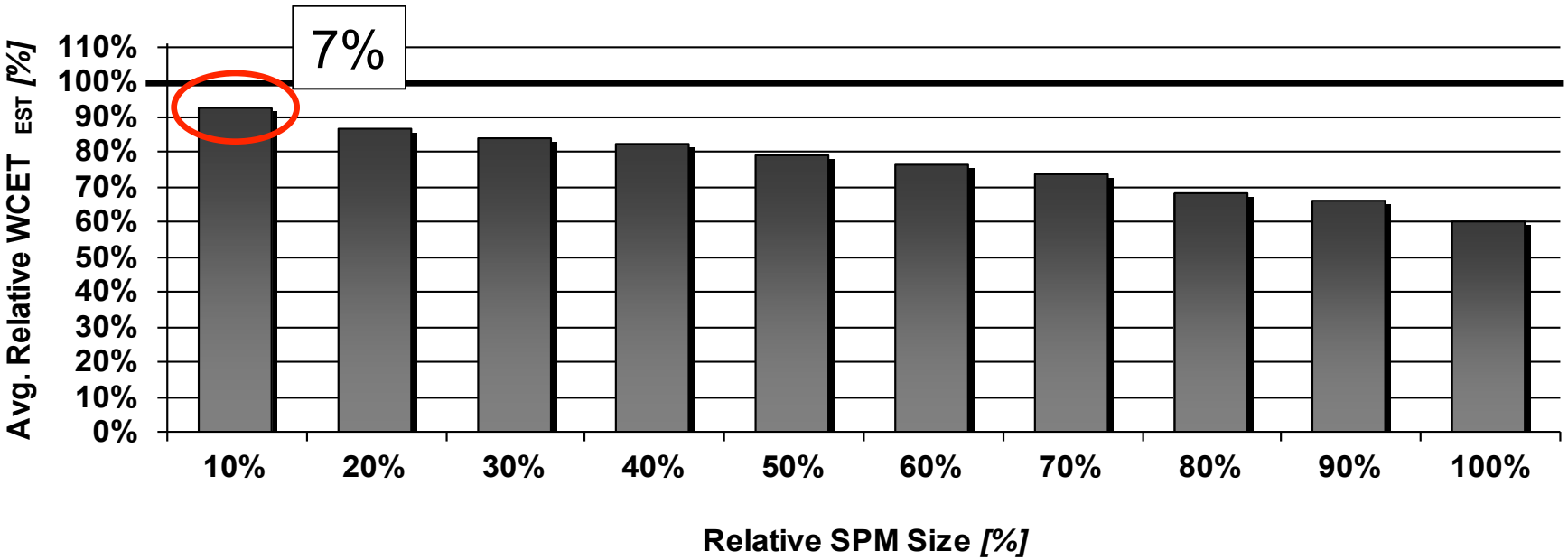
- Size of BB b_i depends on actual jumping code for b_i:
  - Size s_i of jumping code for b_i:
    # bytes for jumping code, depending on jump/call scenario
  - Total size of basic block b_i:
    Size S_i of b_i without any jumping code *plus*
    Size s_i of b_i's jumping code

$$\sum_{b_i}(S_i * x_i + s_i * x_i) \leq S_{spm}$$

Objective Function

- **WCET$_{EST}$ of entire program:**
  - Variable $w_{entry}^{\texttt{main}}$ models WCET$_{EST}$ of entire program
    $w_{entry}^{\texttt{main}} \rightsquigarrow min.$

Average $WCET_{EST}$ for 73 Benchmarks



- Steady $WCET_{EST}$ decreases for increasing SPM sizes
- $WCET_{EST}$ reductions from 7% – 40%

*[**H. Falk, J. Kleinsorge** Optimal Static WCET-aware Scratchpad Allocation of Program Code, DAC 2009]*

Software-based Cache Partitioning

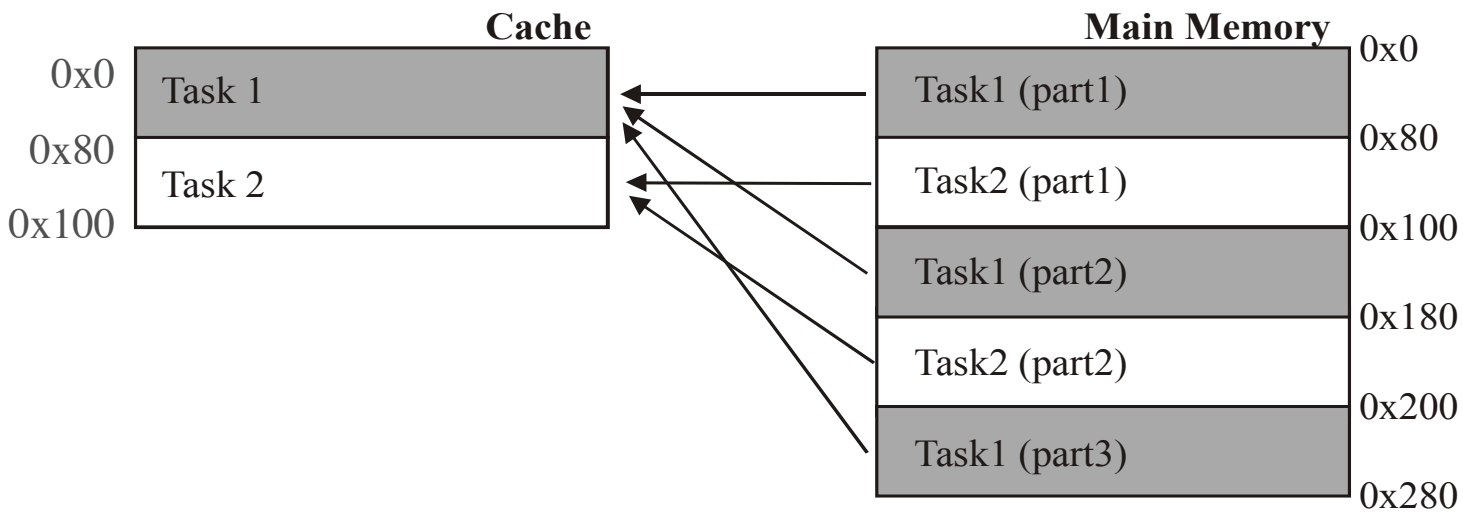
General thoughts on presented optimization strategies:
Until now, greedy relocation successful strategy to get around intra-task cache conflicts due to tight coupling with static WCET analysis
Fails in multi-task environments: Analysis unaware of potential preemptions
Safety can only be achieved by **guaranteeing no collisions**
Granularity: instructions (possibly splitting basic blocks)

Intuition:

Divide the cache into partitions of optimal size
Assign one task per partition to prevent mutual eviction

Software-based Cache Partitioning

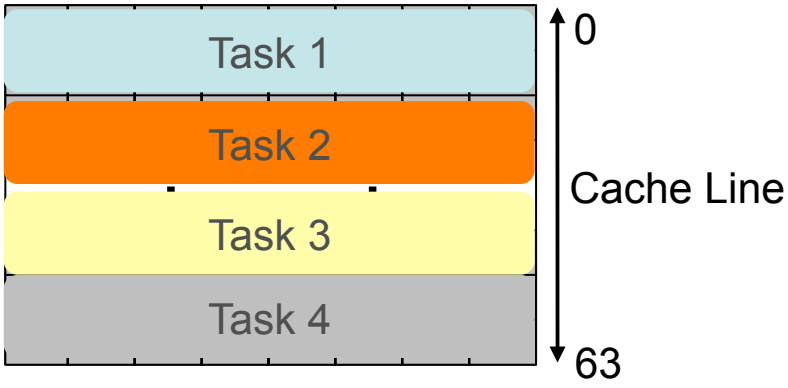
- Exploit the cache addressing logic (index bits)
- Distribute memory blocks of tasks over address space
- Ensure mapping to particular cache lines
  - Effectively inverts the logical mapping direction



WCET-aware Cache Partitioning

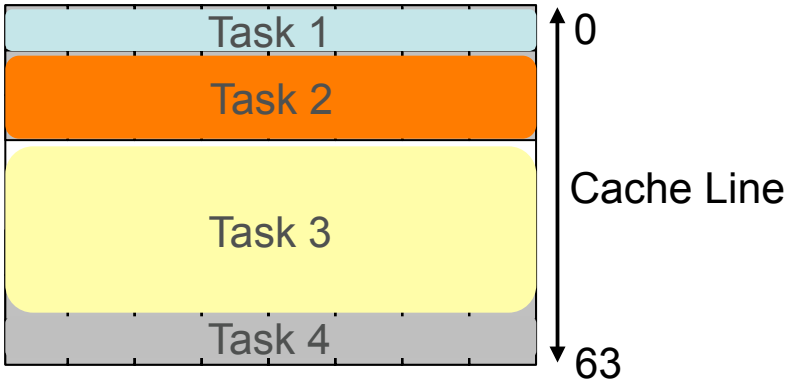
Greedy approach

- Partition size depends on task's code size
- Example: 4 tasks with the same code size



Better

- ILP-model to select individual partition size per task
- Take number of activations into account



*[**F. Müller,** Compiler Support for Software-Based Cache Partitioning, 1995]*