# Compilers for Embedded Systems

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# Chapter 9

# WCET-Aware Compilation

# Outline

# Chapter Contents

# Software Design for Real-Time Systems

**Current Industrial Practice (Automotive, Avionics)**

1. Specification using graphical / high-level tools
2. Automatic generation of ANSI-C code
3. Compilation of binary 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: Go to 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 the impact of optimizations on 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 compiler

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

# Motivation

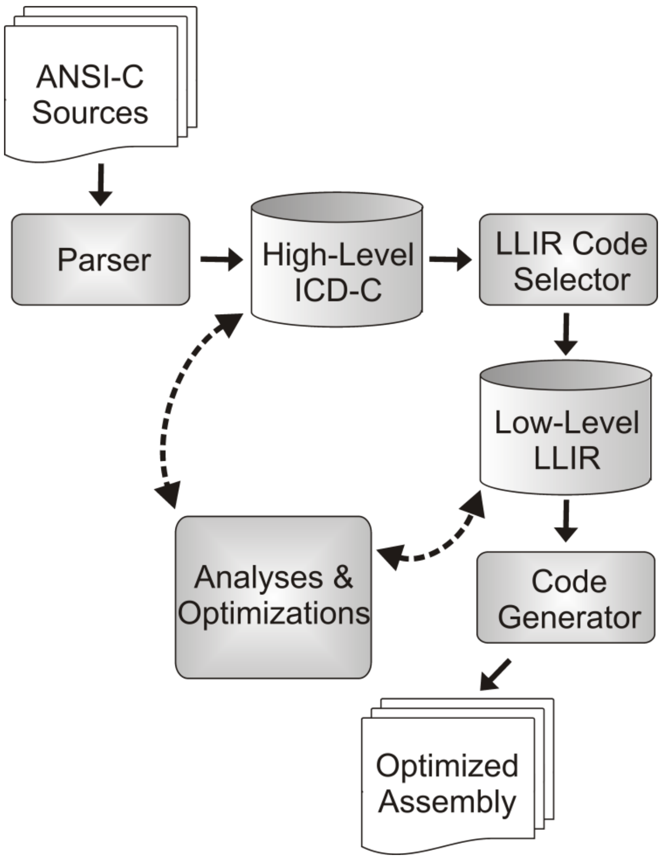
**Design of a Compiler that**

– 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**

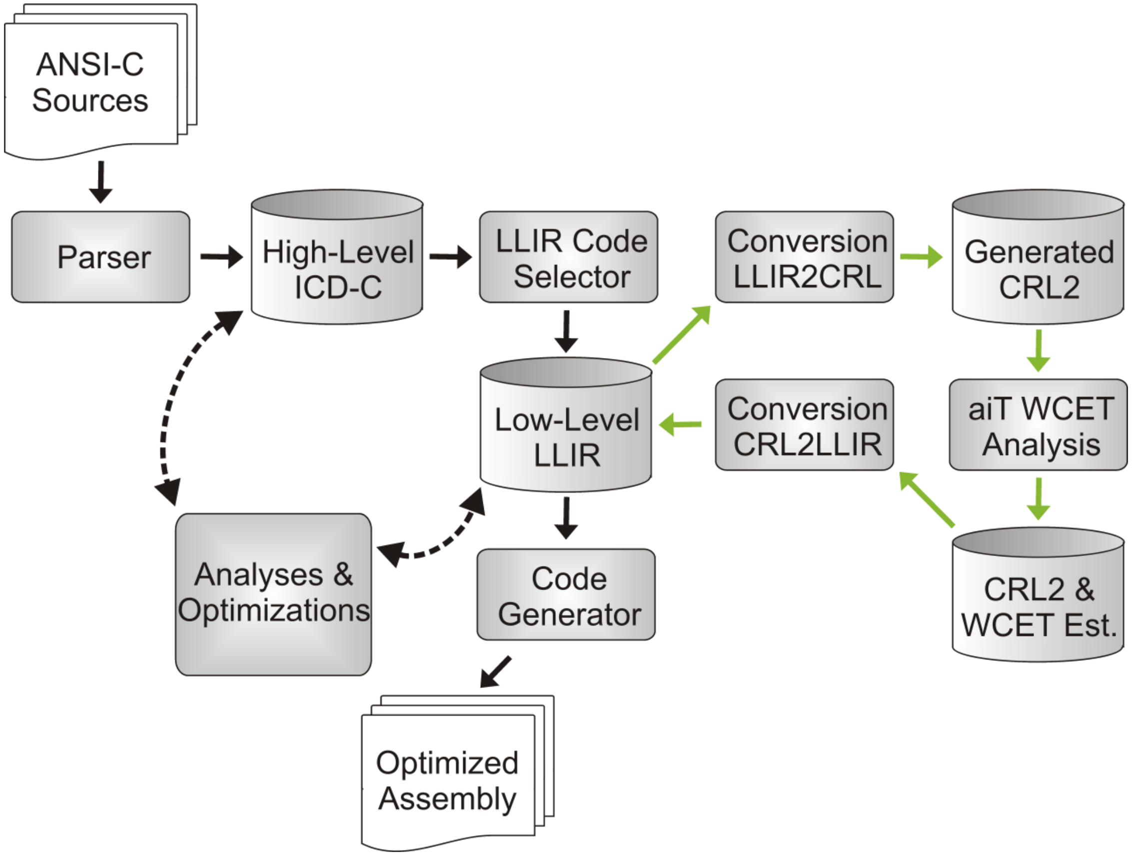
– Integration of a $WCET_{EST}$ timing model into compiler by coupling compiler back-end with static WCET analyzer.
– Exploitation of $WCET_{EST}$ timing model by novel optimizations explicitly aiming at $WCET_{EST}$ minimization.

# Integration of $WCET_{EST}$ Model into Compiler (1)




- Re-implementation of a WCET timing model in compiler makes no sense
- Instead: Tight integration of aiT (☞ *chapter 5)*
- 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

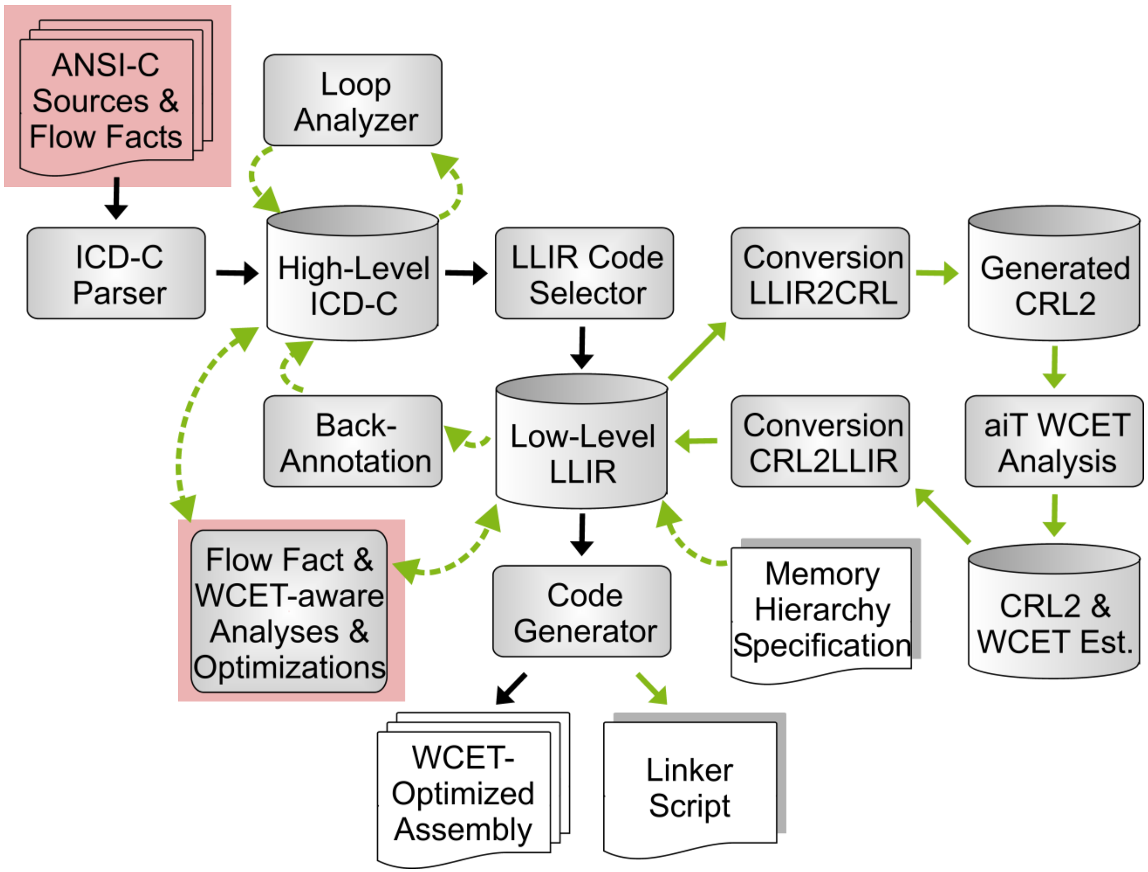
# Integration of $WCET_{EST}$ Model into Compiler (2)




Relevant WCET data:

- $WCET_{EST}$ of entire program, function or basic block
- Worst-case execution frequency per function, basic block or CFG edge
- Potential register contents
- Cache Hits / Misses per basic block

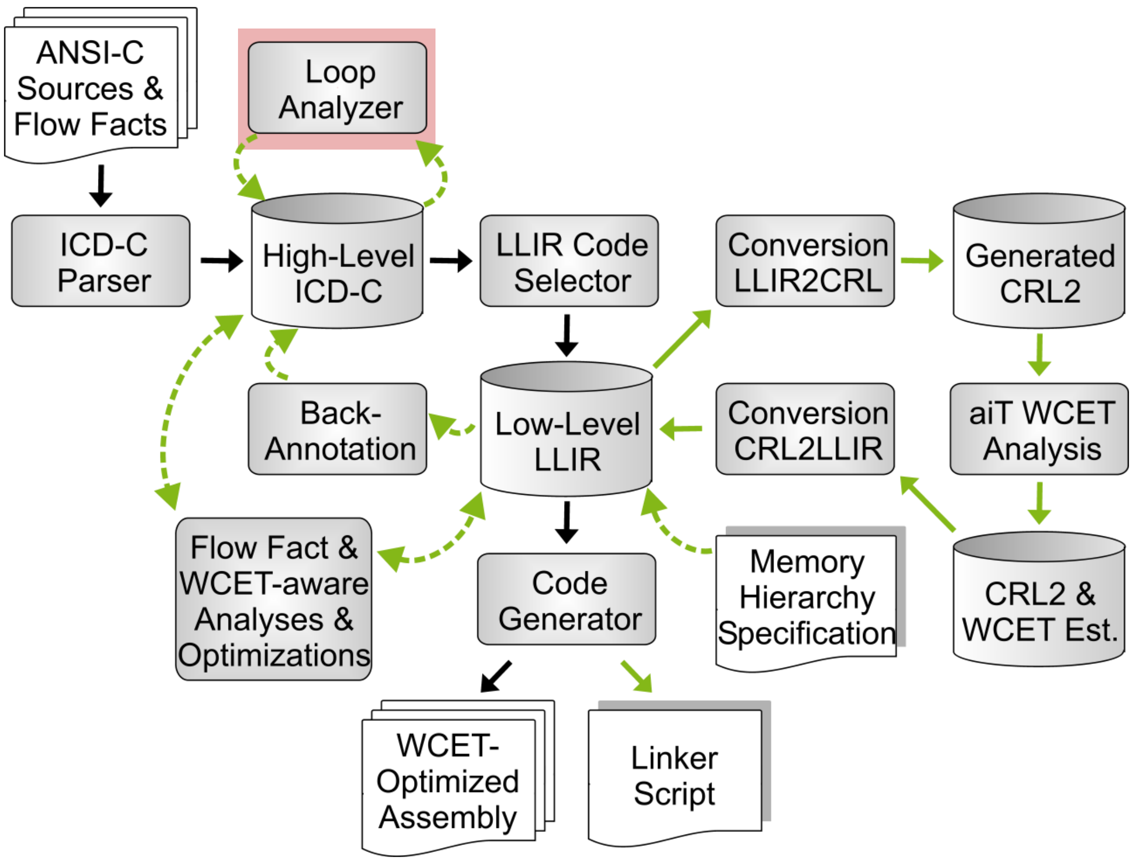
# WCC – The WCET-aware C Compiler (1)




**Flow Facts**

- WCET analysis: max. iteration counts & recursion depths
- WCC: Annotation directly in C source code: `_Pragma( "loopbound min 10 max 10" );`
- Automatic flow fact update during control flow-modifying optimizations

# WCC – The WCET-aware C Compiler (2)



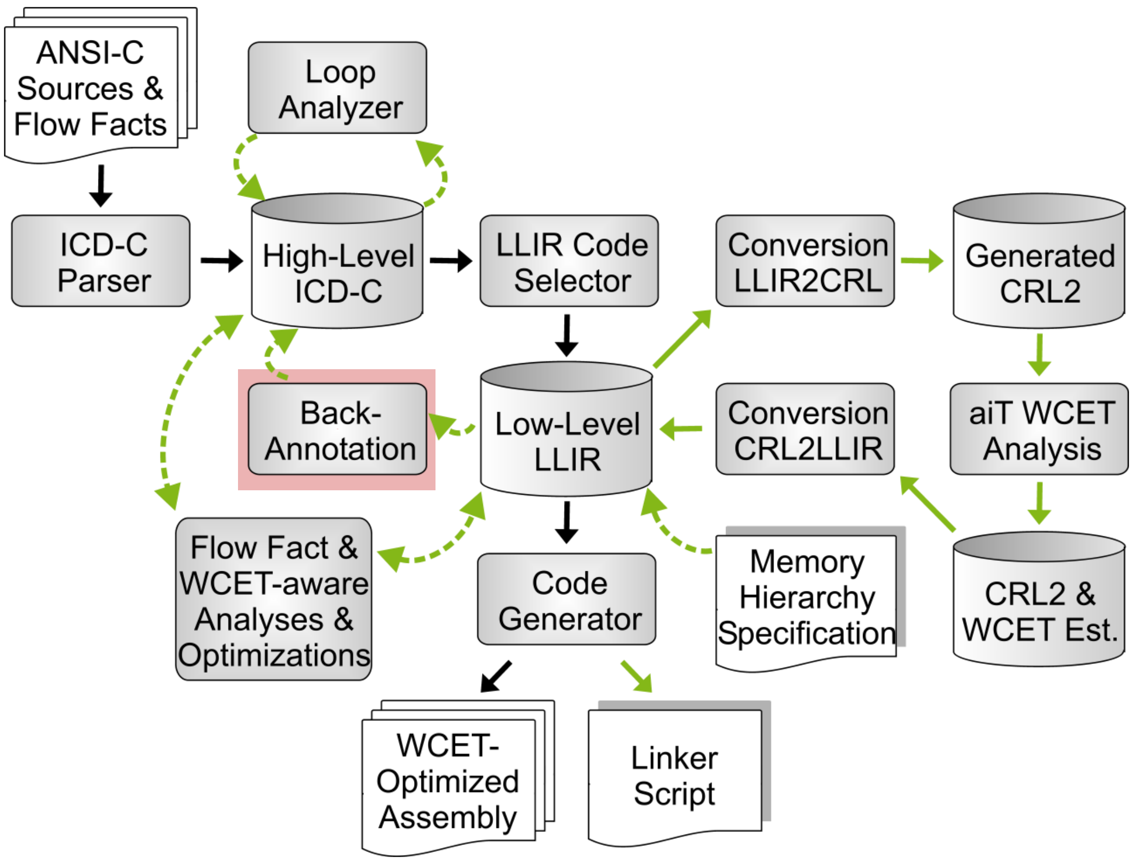

**Loop Analyzer**

– Manual annotation of Flow Facts tedious and error-prone

– WCC: Automated loop analysis that determines maximal iteration counts

– Partially bases on polyhedral models (☞ *chapter 4)*

# WCC – The WCET-aware C Compiler (3)



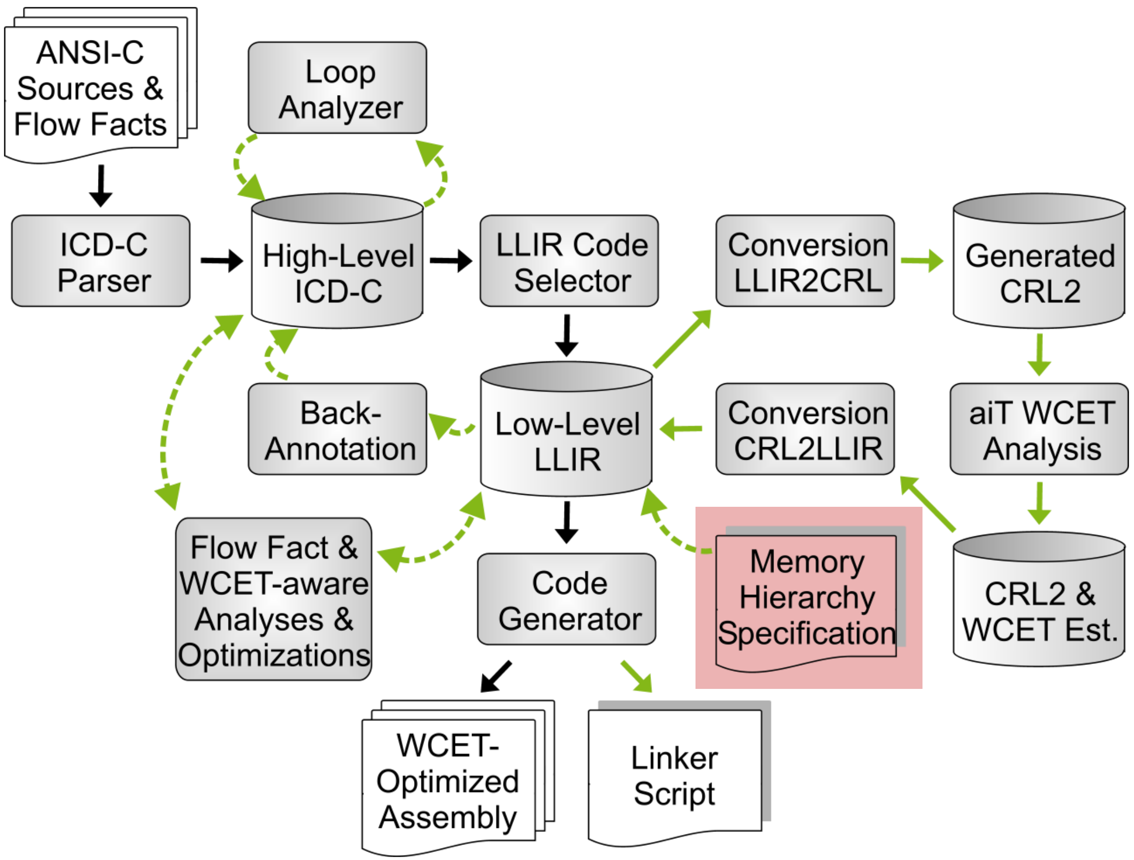

## Back-Annotation

- $WCET_{EST}$ data of aiT only available in back-end
- HIR optimizations have no accesses to $WCET_{EST}$ data

☞ $WCET_{EST}$ minimization at HIR level impossible

- WCC: Back-annotation translates $WCET_{EST}$ data from LIR to HIR

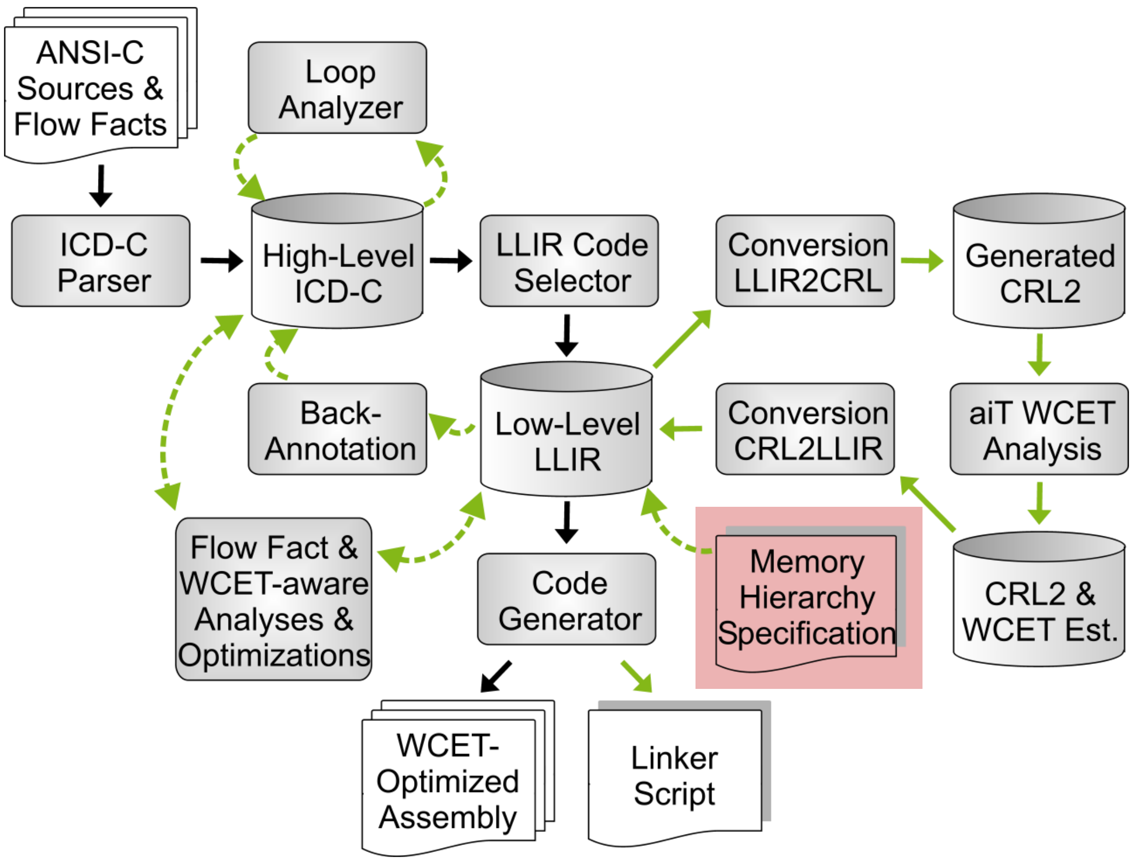
# WCC – The WCET-aware C Compiler (4)




**Memory Hierarchy**

- aiT operates on binary code using physical addresses
- WCC must provide correct physical addresses for code, data, branches and load/store operations to aiT
- WCC requires detailed knowledge about memories

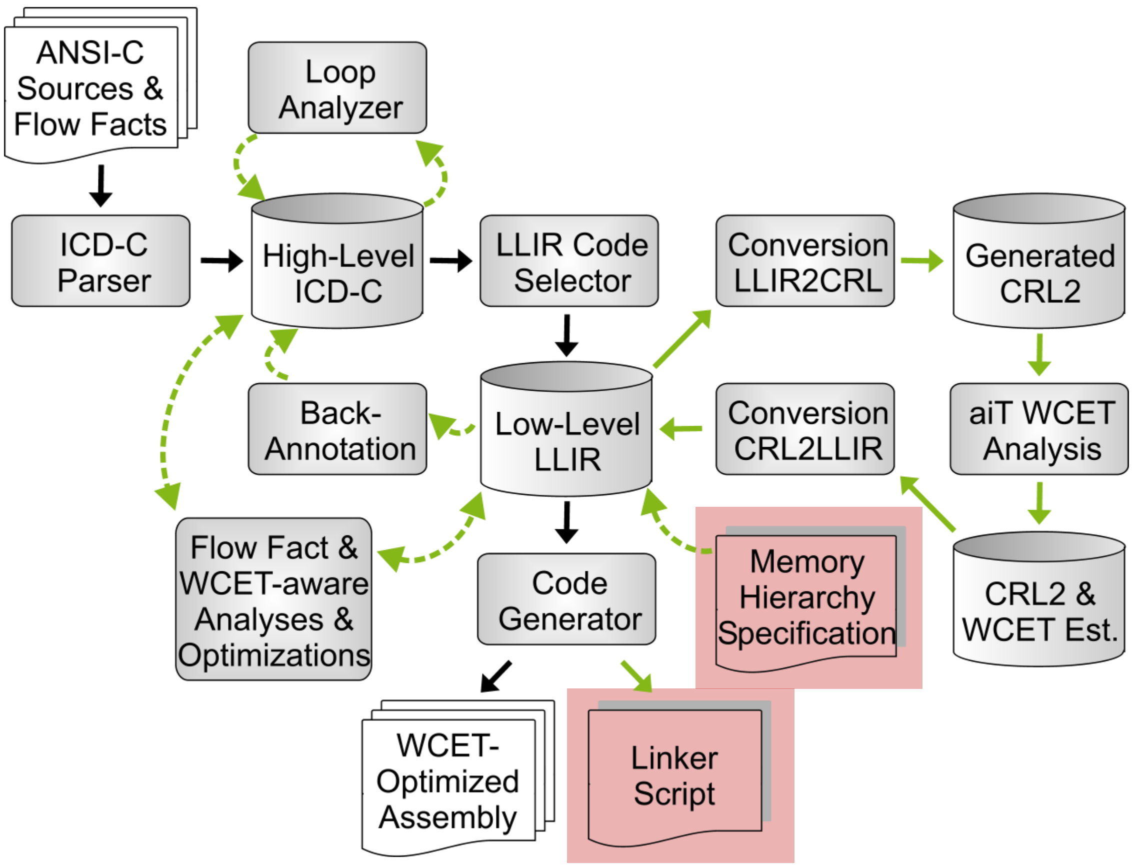
# WCC – The WCET-aware C Compiler (5)




**Memory Hierarchy**

- Memory regions, their start addresses, sizes, access latencies, access attributes (code, data, read-/writable, ...)
- SPM allocations also require this information for their optimizations

# WCC – The WCET-aware C Compiler (6)




**Memory Hierarchy**

- WCC decides on memory layout of code and data but produces no binary code
- Linker must generate binary code in strict compliance with WCC's memory layout
- WCC: Automatic generation of an adapted linker script

[http://www.tuhh.de/es/esd/research/wcc]

# 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 $WCET_{EST}$

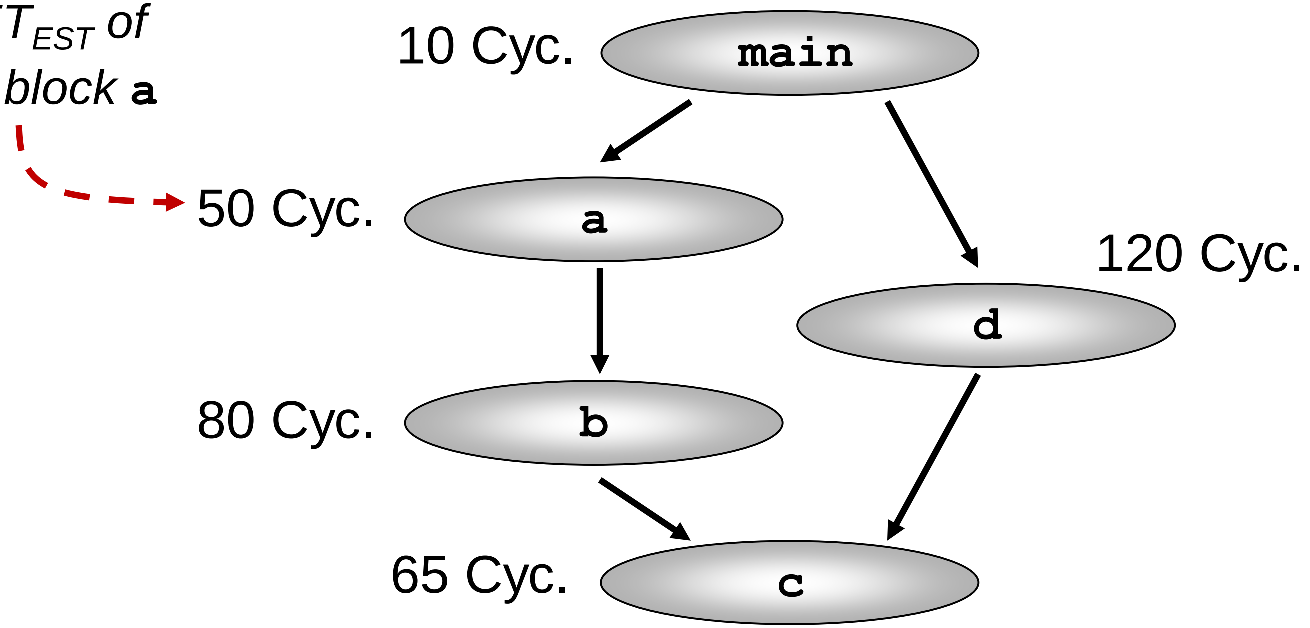
☞ Optimizations minimizing $WCET_{EST}$ require detailed knowledge of the WCEP!

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

*But...*

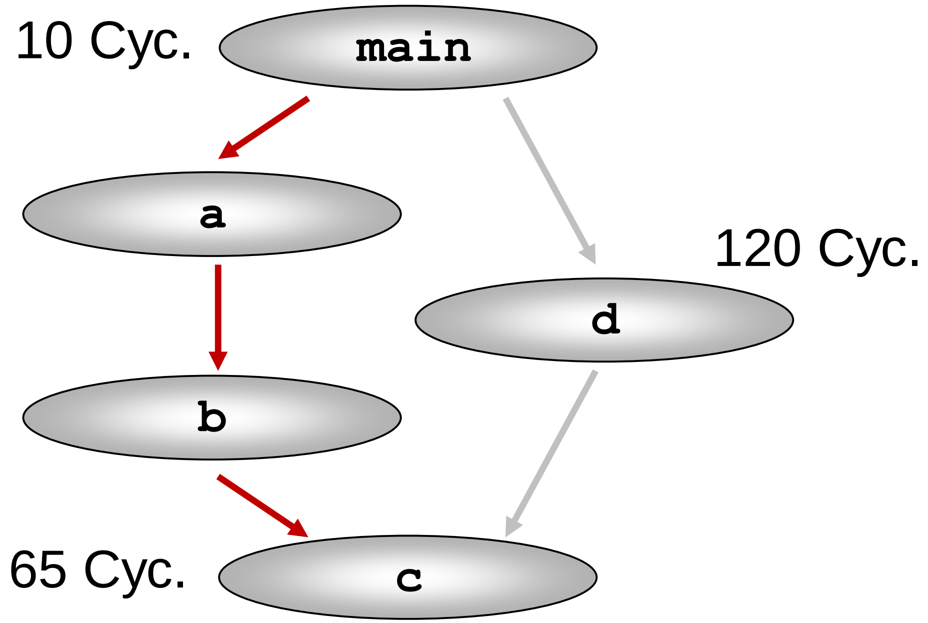
# Instability of the WCEP (1)

*$WCET_{EST}$ of basic block* **`a`**




– Example: Simple CFG with 5 basic blocks

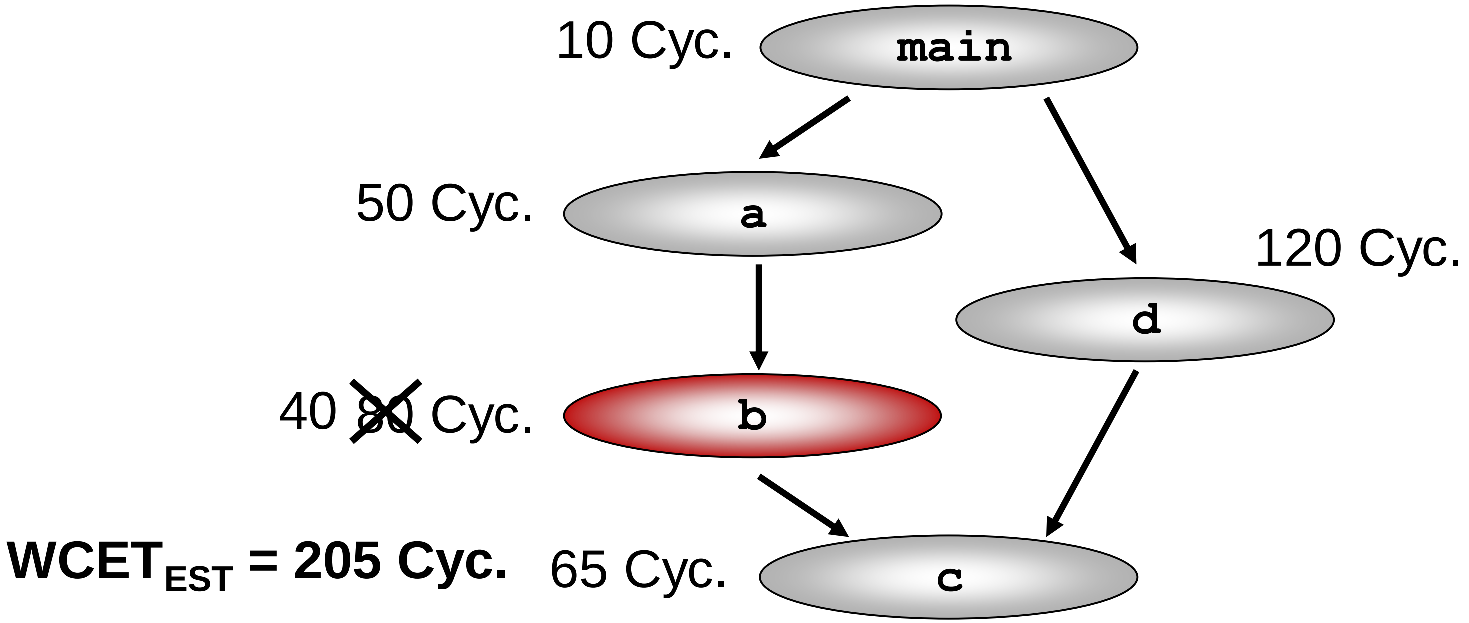
# Instability of the WCEP (2)




**$WCET_{EST}$ = 205 Cyc.**

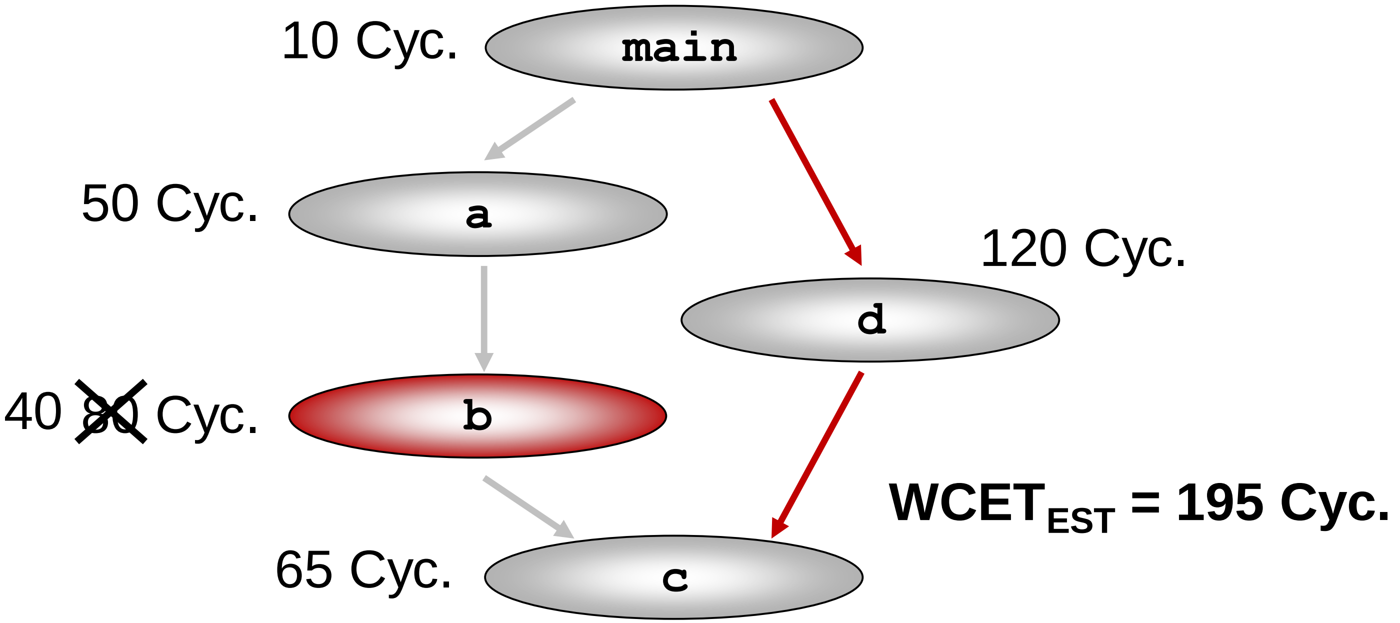
- Initial WCEP: **`main`**, **`a`**, **`b`**, **`c`**
- Length of WCEP = $WCET_{EST}$ = 205
- In the following: Optimization of **`b`**

# Instability of the WCEP (3)




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

# Instability of the WCEP (4)




– Novel WCEP: **`main`**, **`d`**, **`c`**

– Novel $\text{WCET}_{\text{EST}}$: 195

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

# Consequences for Compiler Optimizations

**WCET-Aware Optimizations...**

– ... always have to be aware that the WCEP can change after each individual optimization decision.

– ... should take the decision where to optimize something not only based on local information, but should always consider the global effects of an optimization decision.
*(The optimization of* `b` *in the previous example locally reduces the* $WCET_{EST}$ *of* `b` *by 40 cycles. But globally, only 10 cycles were saved!)*

☞ ***Challenge: To design novel compiler optimizations that fulfill the above requirements and that always consider the entire CFG and the current WCEP therein.***

# Chapter Contents

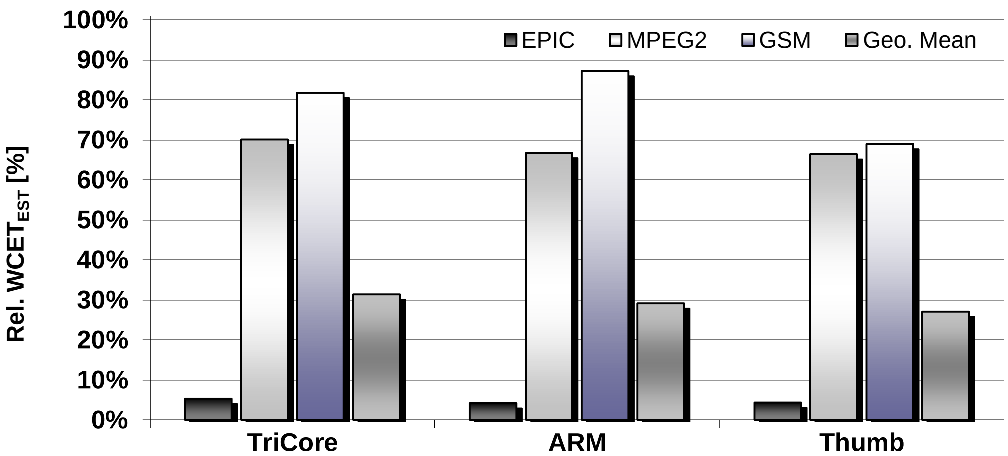
# Why Procedure Cloning and $\text{WCET}_{\text{EST}}$?

**Motivation** *(☞ cf. chapter 5)*

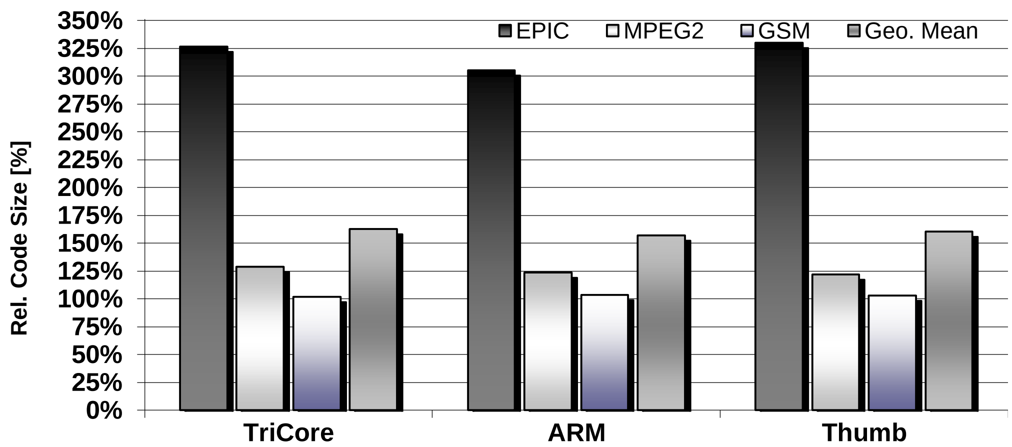
– Frequent occurrences of general-purpose functions in special-purpose contexts in embedded software
– Loop bounds are particularly often controlled by function parameters
– Loop bounds are particularly critical for WCET estimates
– Procedure Cloning allows the extremely precise annotation of loop bounds for WCET analysis

*[**P. Lokuciejewski.** Influence of Procedure Cloning on WCET Prediction. CODES+ISSS, Salzburg, 2007]*

# Results after Classical Cloning




– $WCET_{EST}$ improvements from 13% up to 95%!




– Code size increases from 2% up to 325%!

# Key Problems of Classical Cloning

- $WCET_{EST}$ of a program corresponds to length of WCEP
- Classical Procedure Cloning is fully unaware of WCEP
- Properties of functions that potentially yield $WCET_{EST}$ reductions (parameter-dependent loops) are not considered by the classical standard optimization

☞ Potential cloning of functions that do not lie on the WCEP

☞ Potential cloning of functions that do not contribute to a $WCET_{EST}$ reduction

☞ Unnecessary code size increases without any benefit in terms of $WCET_{EST}$ reduction

# WCET-aware Cloning (1)

**Input**

– Program *P* to be optimized, given in the form of an HIR

– Float value *maxFactor* that denotes the maximally acceptable code size increase

**Initialization**

*maxCodeSize* = getCodeSize( *P* ) * *maxFactor*;

**Phase 1 – Determination of the WCEP**

Perform a WCET analysis of *P*;

Determine set *F* of all original functions lying on the WCEP of *P*;

$wcet_{orig}$ = getWCET( *P* );

$cs_{orig}$ = getCodeSize( *P* );

# WCET-aware Cloning (2)

**Phase 2 – Determination of $WCET_{EST}$ Data per Function**

```
for ( <all functions f ∈ F> )
  if ( <f is called with constant value as some parameter p> &&
      ( <p is used as loop bound> ||
        <p is used in a condition of an if-statement> ||
        <p is argument in some other function call inside f> ) )
    // Cloning of f eventually beneficial w.r.t. WCET_EST
    HIR P' = P.copy();
    doCloning( P', f );                    // Try out cloning of f
    updateLoopBounds( P', f );
    deleteRedundantIfStmts( P', f );
    Perform WCET analysis of P';
    wcet_f = getWCET( P' );
    cs_f = getCodeSize( P' );
```

# WCET-aware Cloning (3)

**Phase 3 – Determination of that Function with highest Profit**

for ( <*all functions* $f \in F$> )

$profit_f = ( wcet_{orig} – wcet_f ) / ( cs_f – cs_{orig} )$;

Determine function $f_{opt}$ with maximal $profit_f$ AND

$cs_f \leq maxCodeSize$;

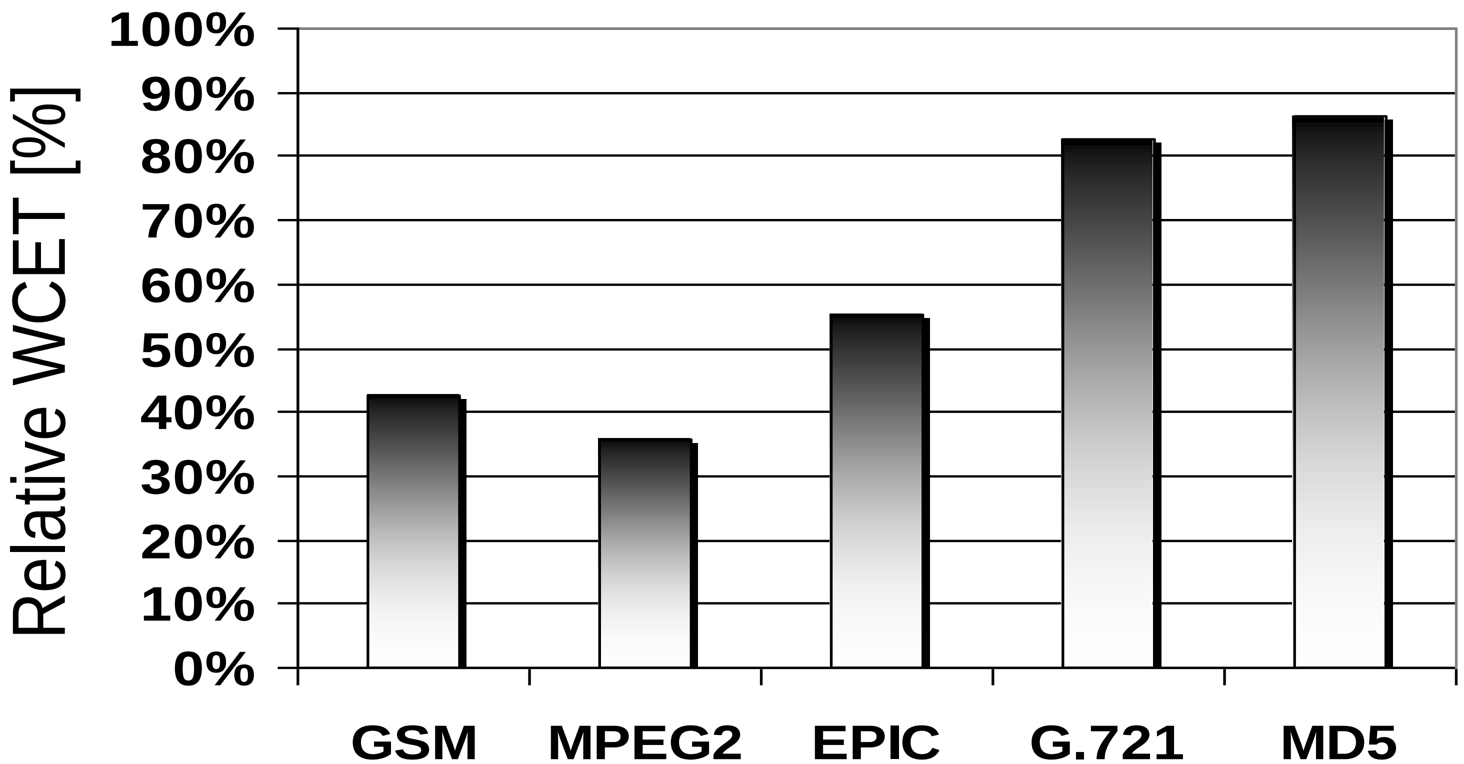
if ( <$f_{opt}$ exists> )

doCloning( $P$, $f_{opt}$ );

goto <*Phase 1*>;

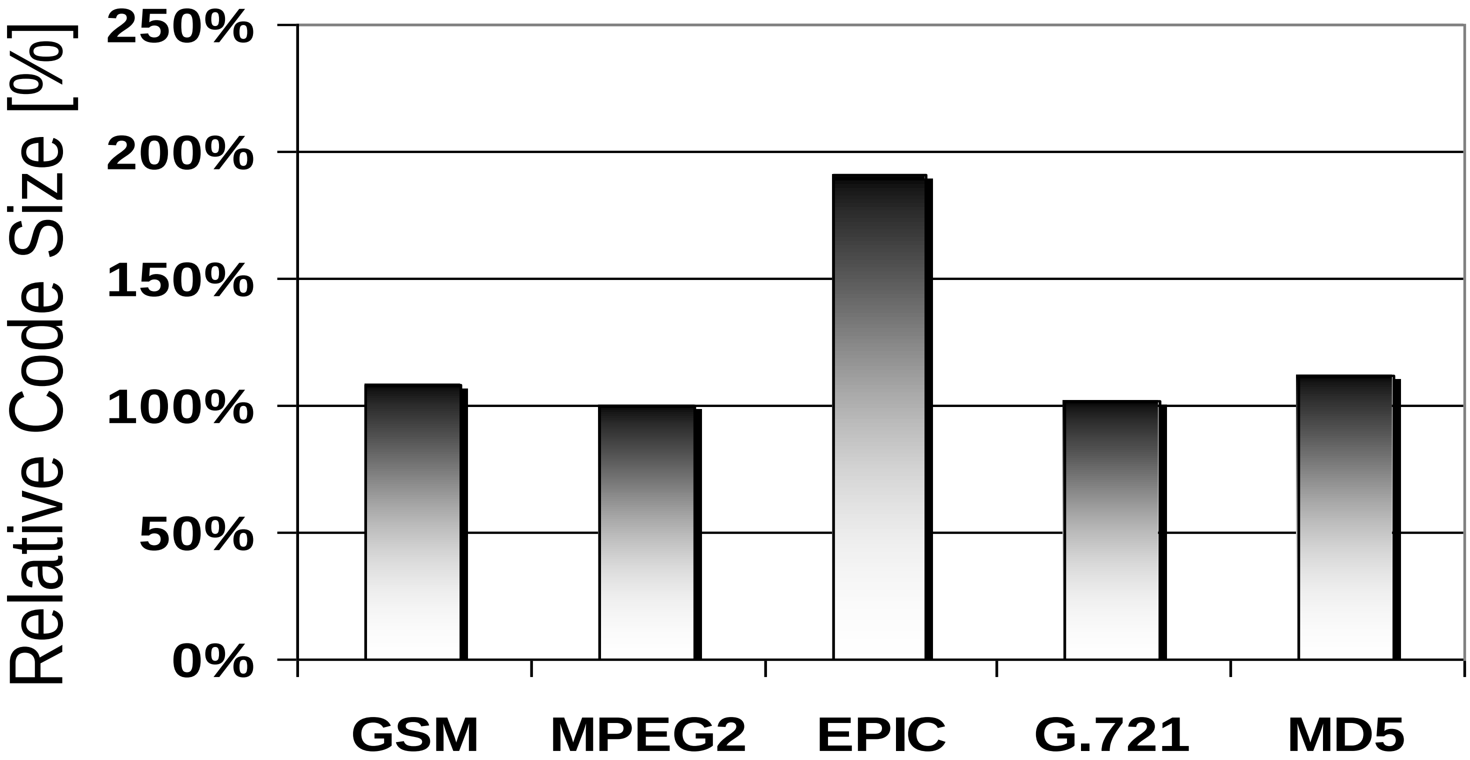
*[**P. Lokuciejewski.** WCET-Driven, Code-Size Critical Procedure Cloning. SCOPES, Munich, 2008]*

# Relative $WCET_{EST}$ after WCET-aware Cloning




- 100% = $WCET_{EST}$ without any procedure cloning
- $WCET_{EST}$ reductions from 14% up to 64%!

# Relative Code Sizes after WCET-aware Cloning

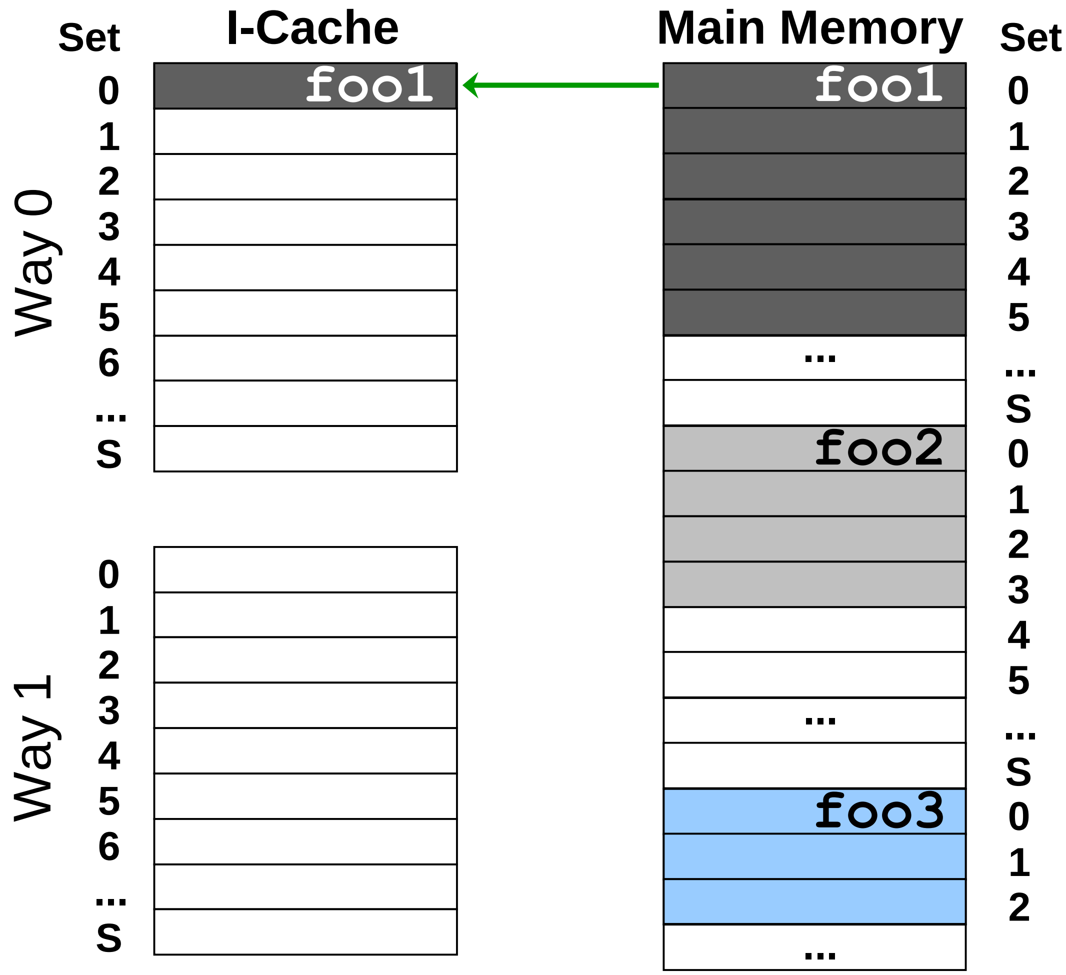



- 100% = Code size without any procedure cloning
- Code size increase of EPIC: 190% instead of 300%

# Eviction of Code from Instruction Caches

- Caches exploit locality of memory accesses
  - *Spatial Locality:* Memory accesses target a spatially small memory region that should be kept in the cache completely
  - *Temporal Locality:* In a short period of time, spatially scattered memory regions are accessed so that these regions should be kept in the cache
- Poor layout of code (or data) in memory can lead to a bad cache performance if temporal locality is high:
- Scattered memory regions with high temporal locality can, when arranged badly in memory, evict themselves repeatedly from the cache, thus yielding many cache misses – so-called *conflict misses*.

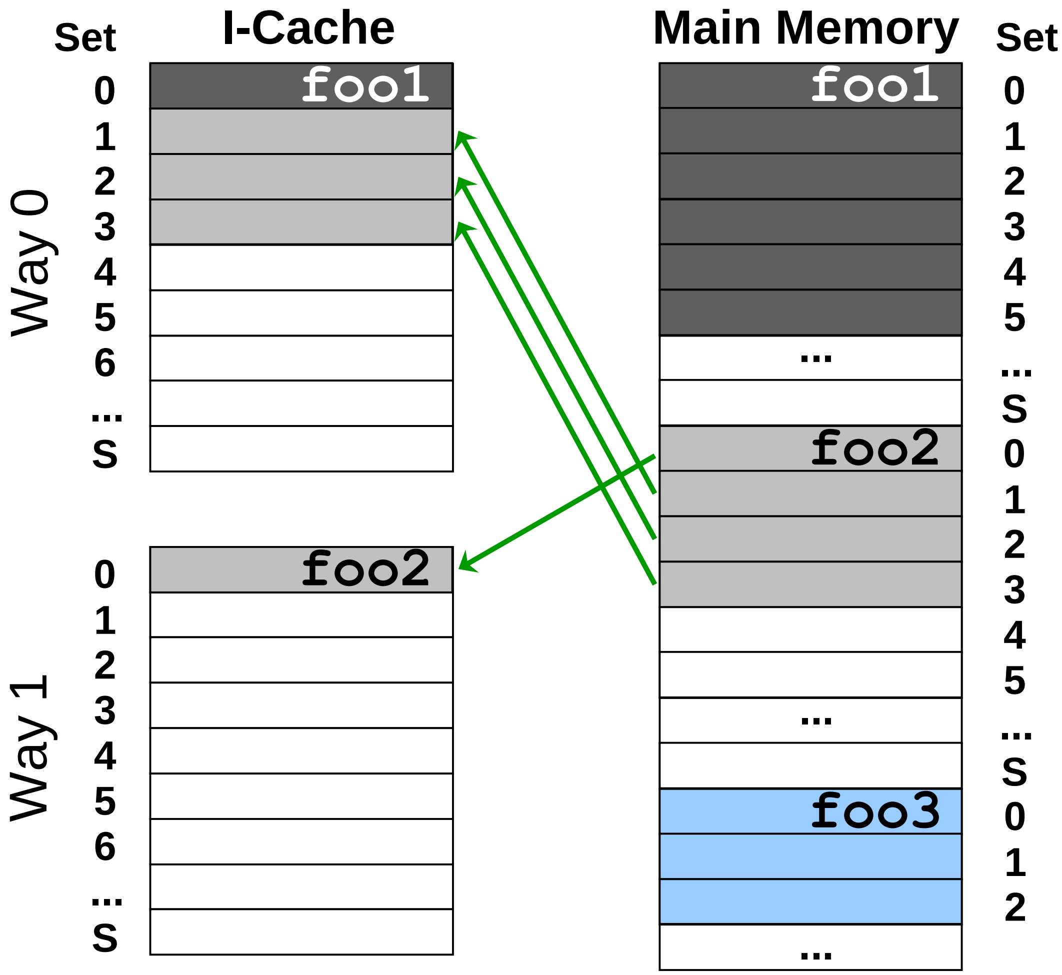
# Example of I-Cache Evictions (1)




```
void foo1()
{
  for (i=0; i<n; i++) {
    foo2();
    foo3();
    // More Code
  }
}
```

*Here:* 2-way set-associative I-Cache

# Example of I-Cache Evictions (2)

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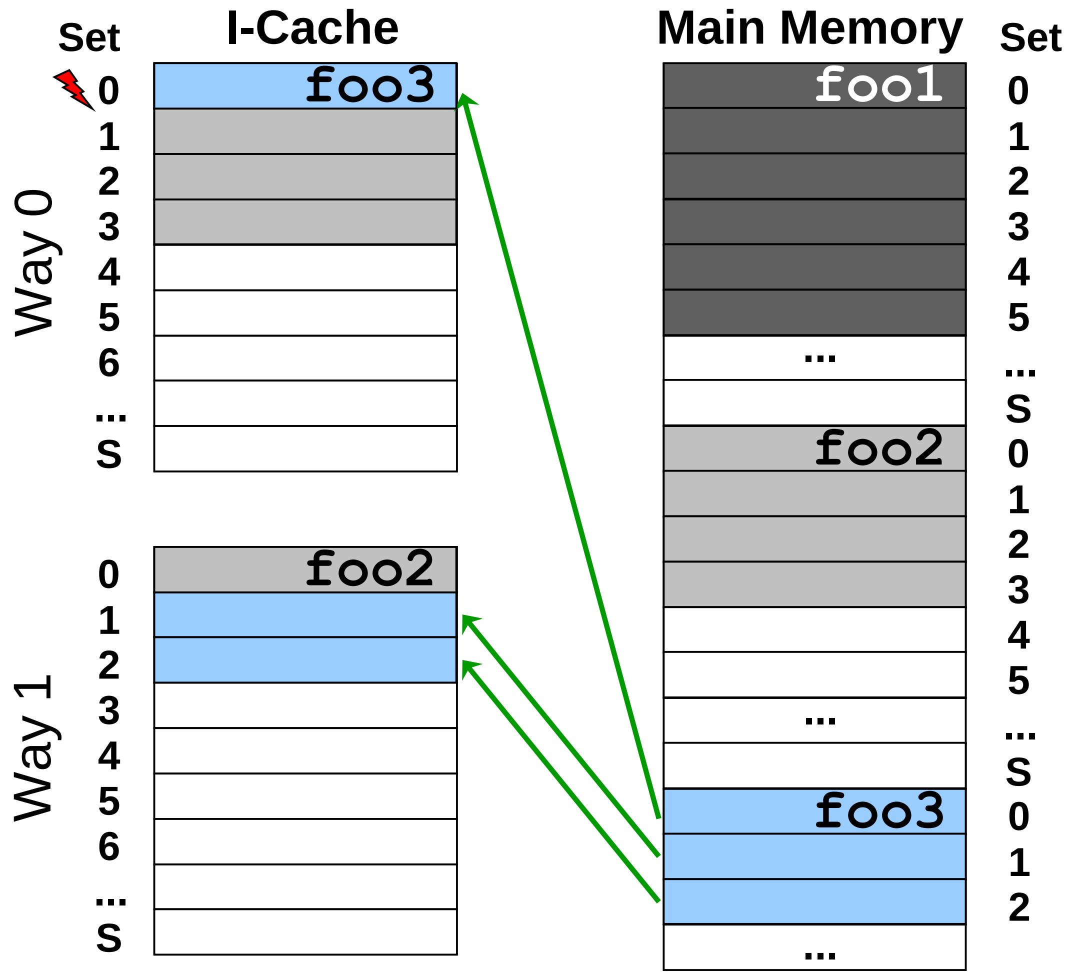
# Example of I-Cache Evictions (3)

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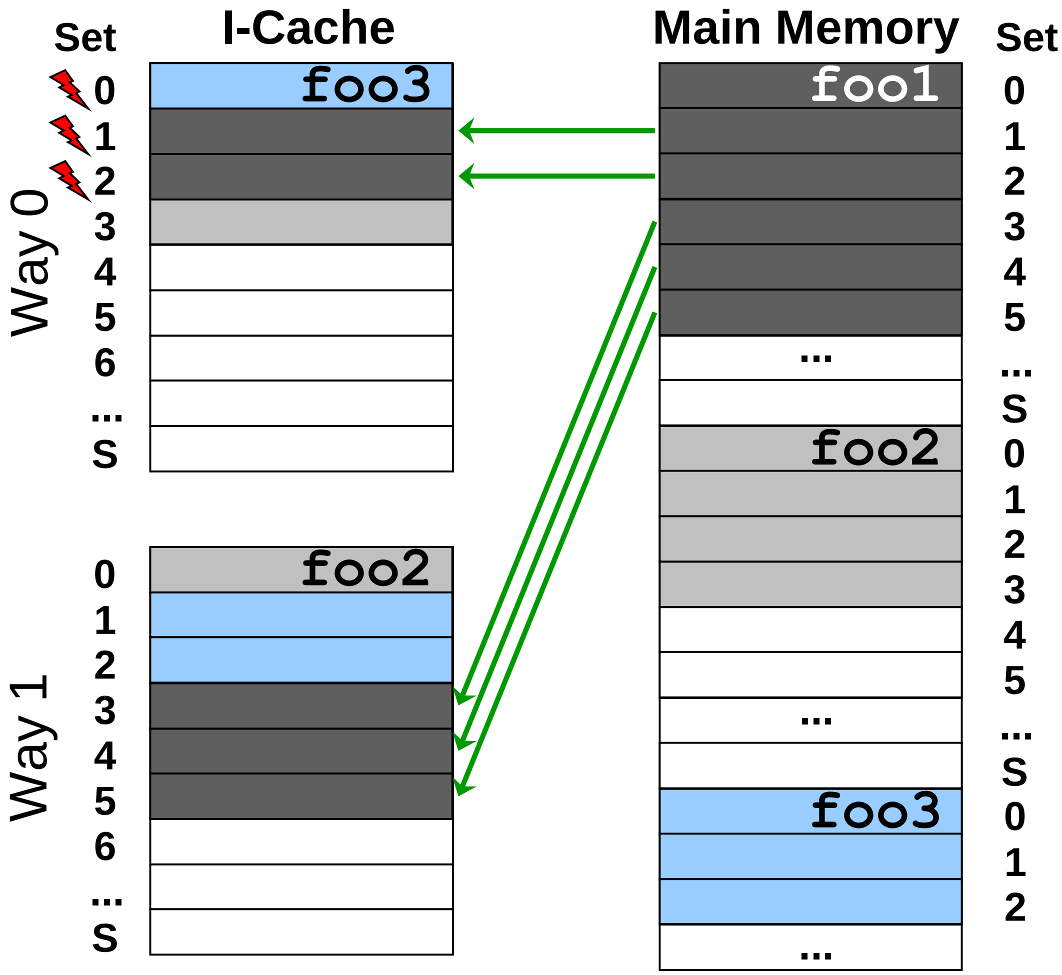
# Example of I-Cache Evictions (4)

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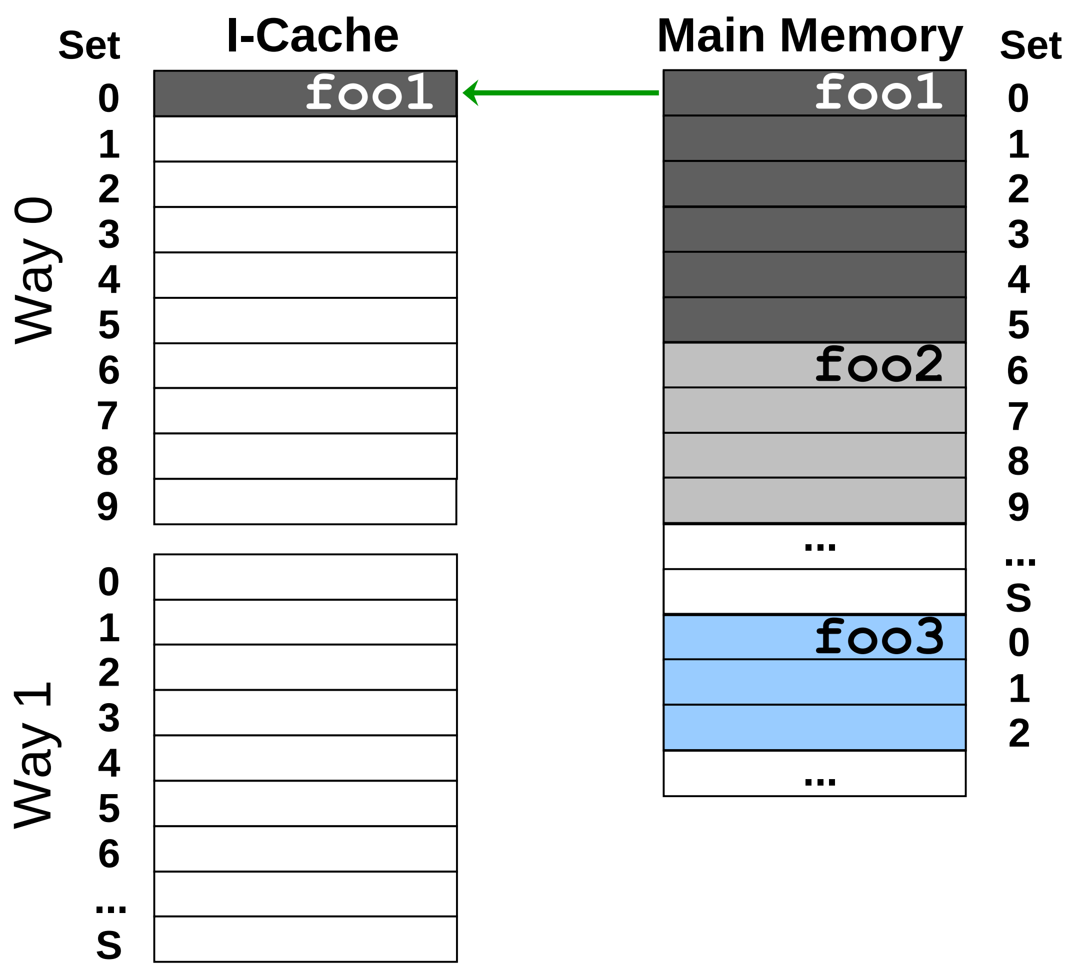
# A better Memory Layout without Evictions (1)

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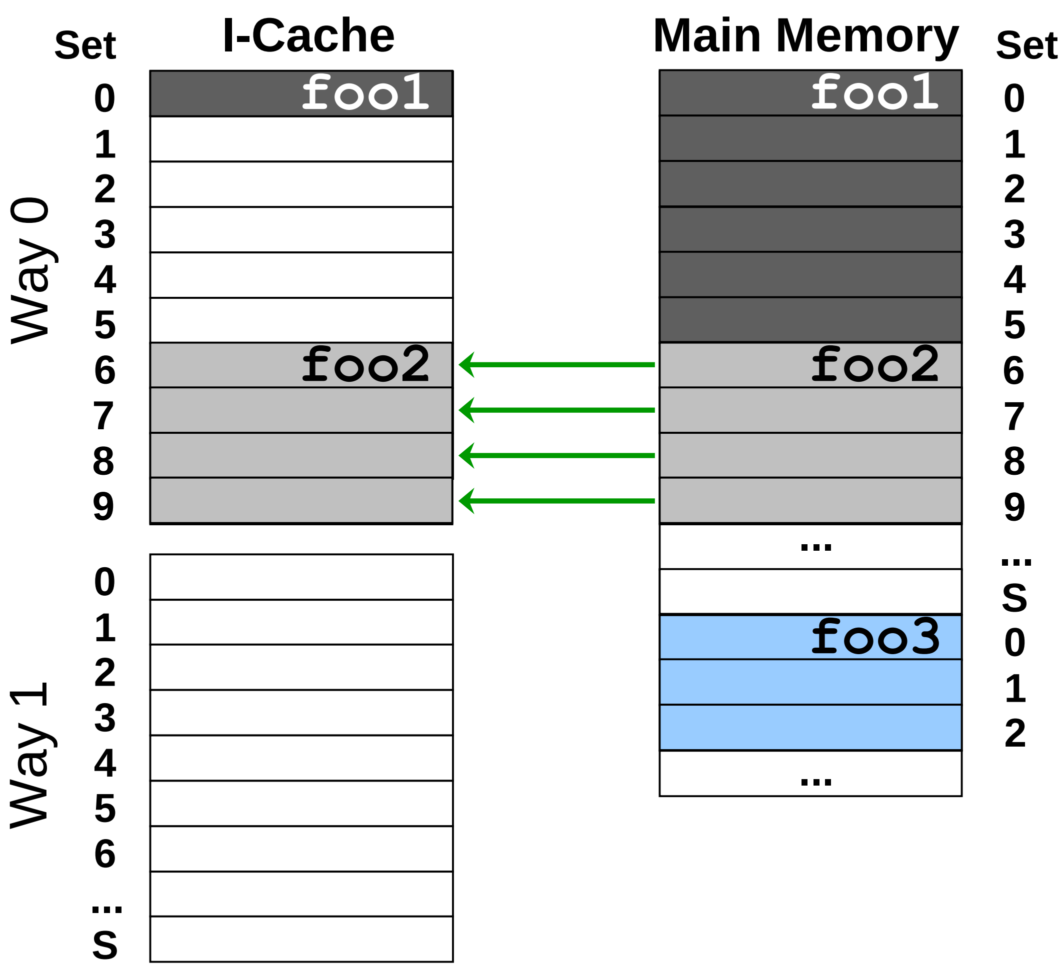
*Here:* 2-way set-associative I-Cache

# A better Memory Layout without Evictions (2)




```
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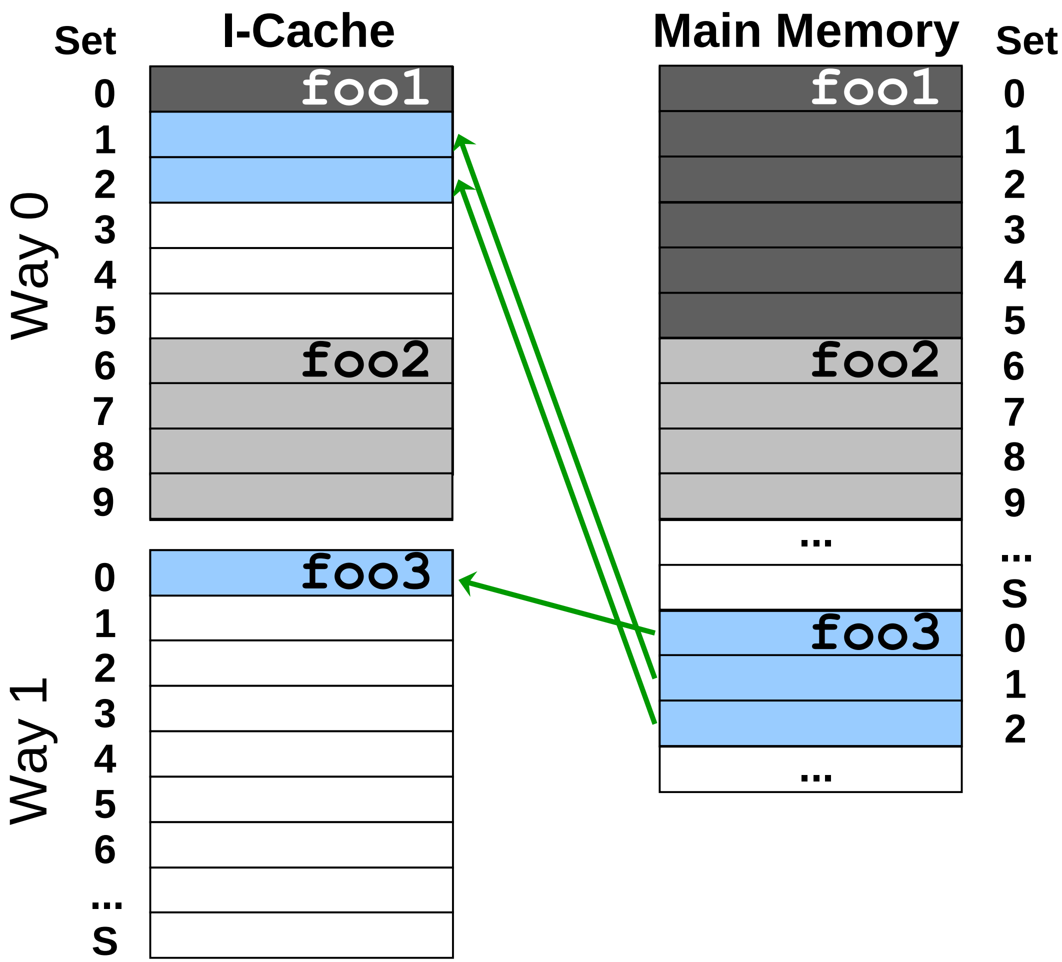
# A better Memory Layout without Evictions (3)

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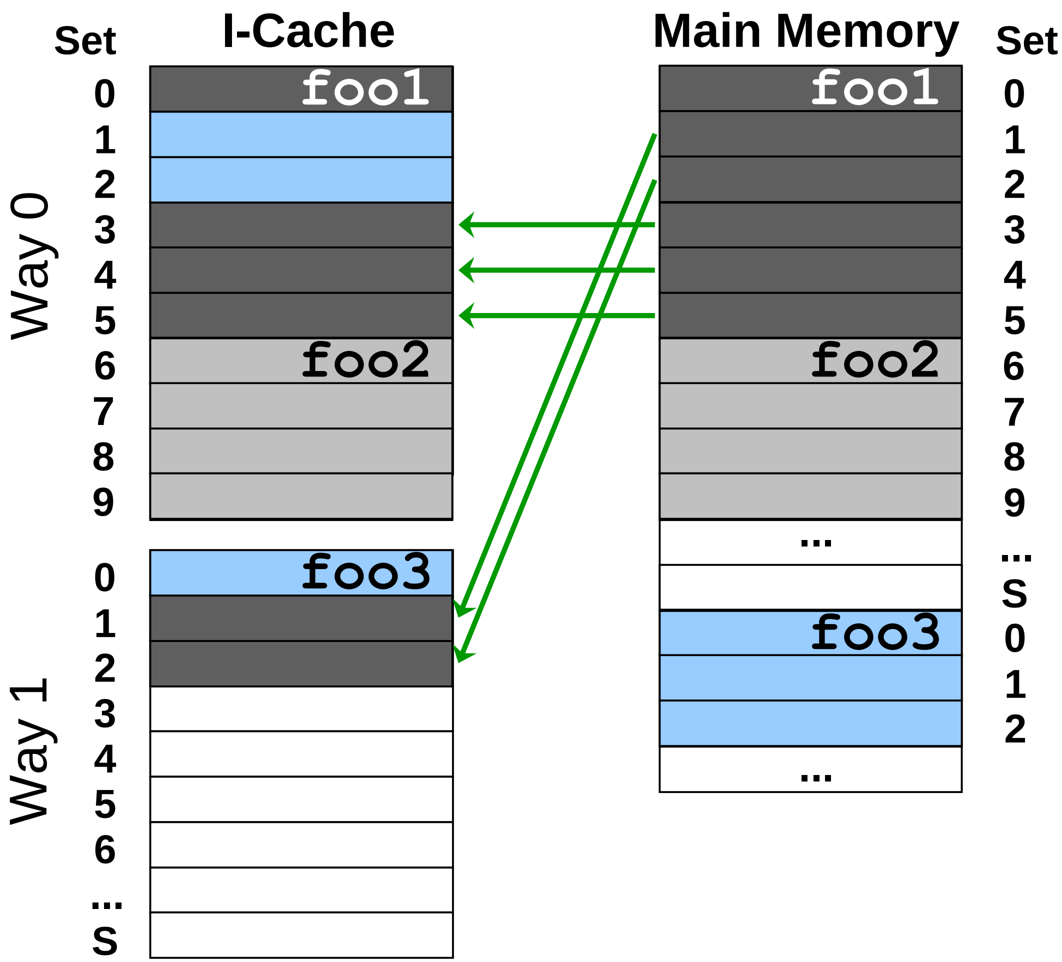


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      // More Code
   }
}
```

*Here:* 2-way set-associative I-Cache

# Procedure Positioning using Call Graphs

**Definition *(Call Graph)*:**

The *Call Graph* is an undirected weighted graph $G = (V, E, w)$ with

- $V$ contains a node $v$ per function of a program
- $E$ contains an edge $e = \{v, w\}$ if a function $v$ calls function $w$
- Each edge $e = \{v, w\}$ is weighted with the frequency $w(e)$ how often $v$ and $w$ call themselves

**Concept of WCET-aware Procedure Positioning**

- Generate call graphs with edge weights equal to worst-case call frequencies as determined during static WCET analysis
- Repeatedly place two functions with high edge weights consecutively in memory

# WCET-aware Procedure Positioning (1)

**Input**

– Program $P$ to be optimized, given in the form of an LIR

**Initialization**

Perform a WCET analysis of $P$;

Generate call graph $G_{orig} = (V_{orig}, E_{orig}, w_{orig})$ of $P$ based on WCET data;

Generate call graph $G_{new} = (V_{new}, E_{new}, w_{new}) = G_{orig}$.copy();

*[**P. Lokuciejewski et al.** WCET-driven Cache-based Procedure Positioning Optimizations. ECRTS, Prague, 2008]*

# WCET-aware Procedure Positioning (2)

**Optimization Loop**

do
  $wcet_{current}$ = getWCET( *P* );
  for ( <*all edges e* = {*v*, *w*} $\in$ $E_{new}$,
      *sorted in descending order w.r.t.* $w_{new}$> )
    if ( Positioning( *e*, $G_{new}$, $G_{orig}$, *P*, $wcet_{current}$ ) == true )
      *// If contiguous placement of nodes v and w in memory reduces*
      *// $WCET_{EST}$, terminate for-loop and continue with do-while-loop.*
      break;
while ( <*P was modified during last iteration*> );

# WCET-aware Procedure Positioning (3)

**Positioning(** $e = \{v, w\} \in E_{new}, G_{new}, G_{orig}, P, wcet_{current}$ **)**

Generate LIR *P'* with *v* and *w* placed contiguously in memory;

Perform a WCET analysis of *P'*;

$wcet_{new}$ = getWCET( *P'* );

if ( $wcet_{new} < wcet_{current}$ )

  *P* = *P'*;

  Merge nodes *v* and *w* in $G_{new}$;

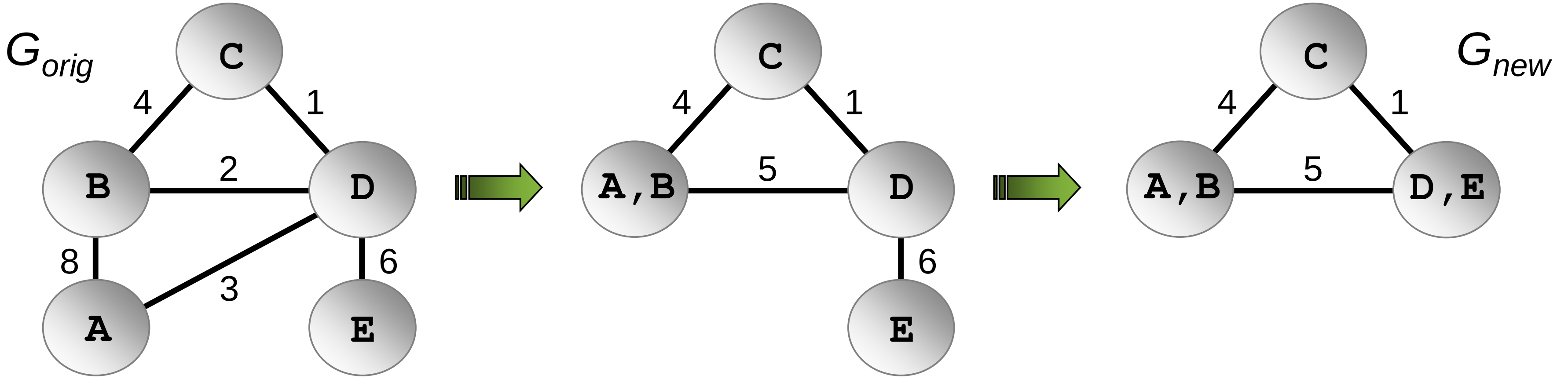
  Update $w_{new}$ based on novel WCET data;

  return true;

else

  return false;

# Merging of Nodes




**Contiguous Placement of merged Nodes in Memory**

– Problem: How shall (**A**, **B**) and (**D**, **E**) be placed in the next step?

– $G_{orig}$ reveals that **A** and **D** should be placed contiguously

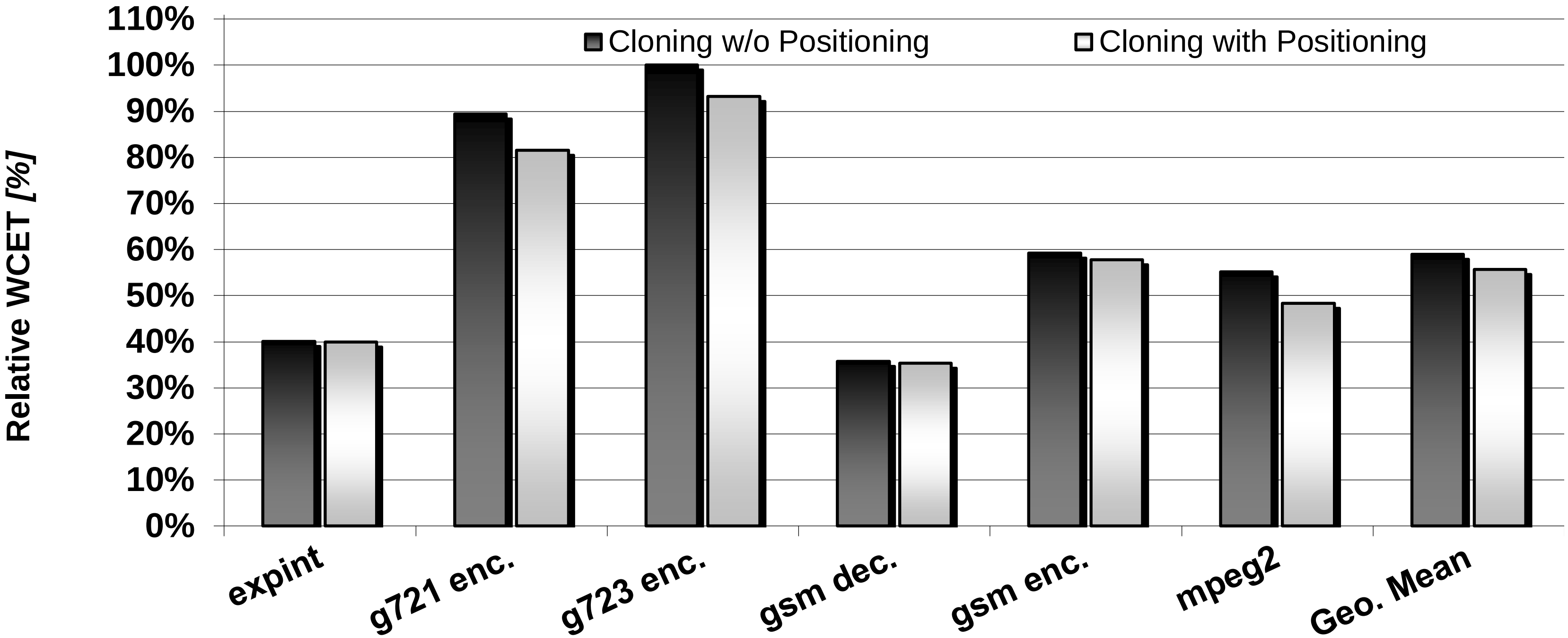
☞ Best placement is (**B**, **A**, **D**, **E**).

☞ That's why $G_{orig}$ is kept throughout the positioning algorithm!

# Properties

- Algorithm greedily places two nodes of the current graph $G_{new}$ contiguously in memory in one iteration
- Here, always those two nodes are considered which call themselves most frequently according to $w_{new}$
- Instable WCEPs are considered by the algorithm, because a WCET analysis is done for each placement, and because the edge weights $w_{new}$ are updated according to this novel WCET data
- Since WCET-aware Procedure Cloning places the novel clones at the end of a program, it makes sense to combine WCET-aware Cloning and Positioning

# Relative $WCET_{EST}$ after WCET-Cloning & Positioning




– 100% = $WCET_{EST}$ w/o Procedure Cloning and Positioning
– I-Cache: 16kB, 2-way set-associative, LRU replacement
– WCET-Positioning of clones: additional $WCET_{EST}$ reduction by up to 7% compared to cloning w/o positioning

***Caution:*** *Don't compare this diagram with slide 30, since I-cache was disabled in slide 30!*

# Conclusions

**Comparison with Consequences for $\mathbf{WCET_{EST}}$ Optimizations**

WCET-aware optimizations...

- ... mandatorily need detailed knowledge of the WCEP
- 👍 *WCET-Cloning and WCET-Positioning both consider the WCEP*
- ... always have to be aware that the WCEP can change after each individual optimization decision
- 👍 *Both optimizations update the WCEP after each modification of the code*
- ... should take the decision where to optimize something not only based on local information, but should always consider the global effects of an optimization decision
- 👎 *WCET-Cloning and WCET-Positioning are both greedy heuristics that are driven solely by local data per function*

# Chapter Contents

# Register Allocation by Graph Coloring

1. **Build:** Create interference graph $G = (V, E)$ with
   $V$ = {*virtual registers*} ∪ {*K physical processor registers*},
   $e = (v, w) \in E \Leftrightarrow$ VREGs *v* and *w* may never share the same PHREG,
   i.e. *v* and *w* interfere
2. **Simplify:** Remove all nodes $v \in V$ with degree $< K$
3. **Spill:** After step 2, each node of *G* has degree $\geq K$. Select one node $v \in V$; mark *v* as *potential spill*; remove *v* from *G*
4. **Repeat** Simplify and Spill until $G = \emptyset$
5. **Select:** Re-insert nodes *v* into *G* in reverse order; if there is a free color $k_v$, color *v*; otherwise, mark *v* as *actual spill*
6. **Generate Spill Code** before/after actual spills; go to step 1 if #VREGS > 0

*[**A. W. Appel.** Modern compiler implementation in C. 2004]*

# Problem of Standard Graph Coloring

3. **Spill:** After step 2, each node of *G* has degree ≥ *K*. Select one node *v* ∈ *V*; mark *v* as *potential spill*; remove *v* from *G*

***Which node v should be selected as potential spill?***

Common graph coloring implementations select ...

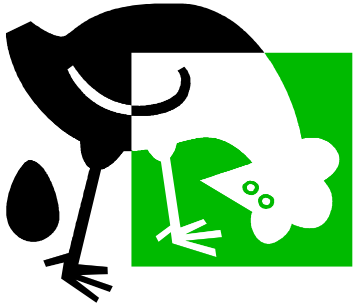
– ... the first node *v* according to the order in which VREGs were generated during code generation,

– ... the node with highest degree in the interference graph,

– ... a node with high degree, with few DEFs/USEs, not in some inner loop – maybe depending on profiling data.

***Uncontrolled spill code generation – potentially along Worst-Case Execution Path (WCEP) defining the WCET!***

# A Chicken-Egg Problem



**A WCET-aware Register Allocator...**

– ... relies on WCET data provided by WCET analysis using aiT,
– ... but cannot obtain WCET data since code containing virtual registers is not executable and thus not analyzable!

**The Way Out**

– Start by marking all VREGs as actual spill
  ☞ Code has lousy quality, but is fully analyzable
– Perform WCET analysis, get WCEP *P*
– Apply standard graph coloring to all VREGs of that basic block $b \in P$ with most executions of spill code in the worst case
– Re-evaluate novel WCEP

# WCET-aware Graph Coloring (1)

```
LLIR WCET_GC_RA( LLIR P )
{
  // Iterate until current WCEP is fully allocated.
  while ( true )
  {
    // Copy P, spill all VREGs of P′ onto stack.
    LLIR P′ = P.copy();
    P′.spillAllVREGs();

    // Compute Worst-Case Execution Path for fully spilled LIR.
    set<basic_blocks> WCEP = computeWCEP( P′ );

    // If there are no more VREGs, the allocation loop is over.
    if ( getVREGs( WCEP ) == ∅ )
      break;
```

# WCET-aware Graph Coloring (2)

```
    // Determine that block on the WCEP with highest product of
    // Worst-Case Execution Count * spilling instructions.
    basic_block b′ = getMaxSpillCodeBlock( WCEP );
    basic_block b = getBlockOfOriginalP( b′ );

    // Collect all VREGs of this most critical block.
    list<virtualRegister> vregs = getVREGs( b );

    // Sort VREGs by #occurrences, apply standard graph coloring.
    vregs.sort( occurrences of VREG in b );
    traditionalGraphColoring( P, vregs );
  }

  // Allocate all remaining VREGs not lying on the WCEP.
  traditionalGraphColoring( P, getVREGs( P ) );
  return P;
}
```

# Properties (1)

- Algorithm simultaneously handles a program *P* to be register allocated, and a copy *P'* where all VREGs are completely spilled to memory in order to enable WCET analysis.
- Register allocation is done basic block-wise along the WCEP.
- After the allocation of one basic block, the WCEP in *P'* is recomputed.
- In one iteration of the algorithm: Allocation of all VREGs occurring in that basic block *b* that contains many spill instructions in *P'* and that is executed very often.

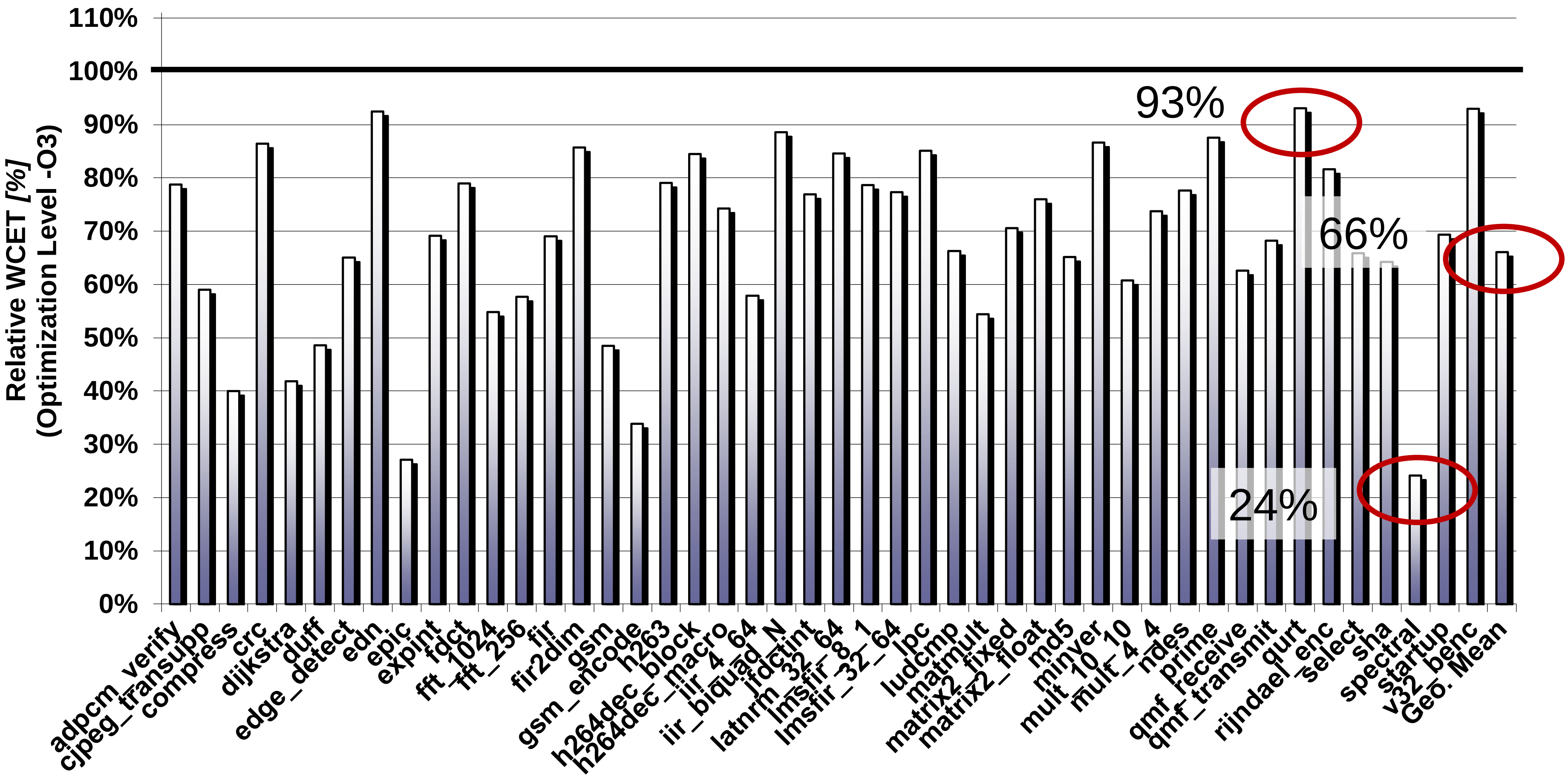
☞ The VREGs of this most timing-critical block *b* should be kept in PHREGs if possible.

# Properties (2)

– Spilling of VREGs in *b* cannot be avoided in general. If spilling is required in *b*, spill only those VREGs *v* of *b* that occur least frequently in *b*, since few occurrences of *v* in *b* imply few spill instructions inside *b*.
– Register allocation itself, i.e., assigning colors to *b*'s VREGs, and spill code generation are handed over to standard graph coloring.
– After the allocation loop, the WCEP is completely allocated. But there may still be some VREGs in blocks besides the WCEP.
☞ One final run of standard graph coloring in order to catch all those remaining VREGs.

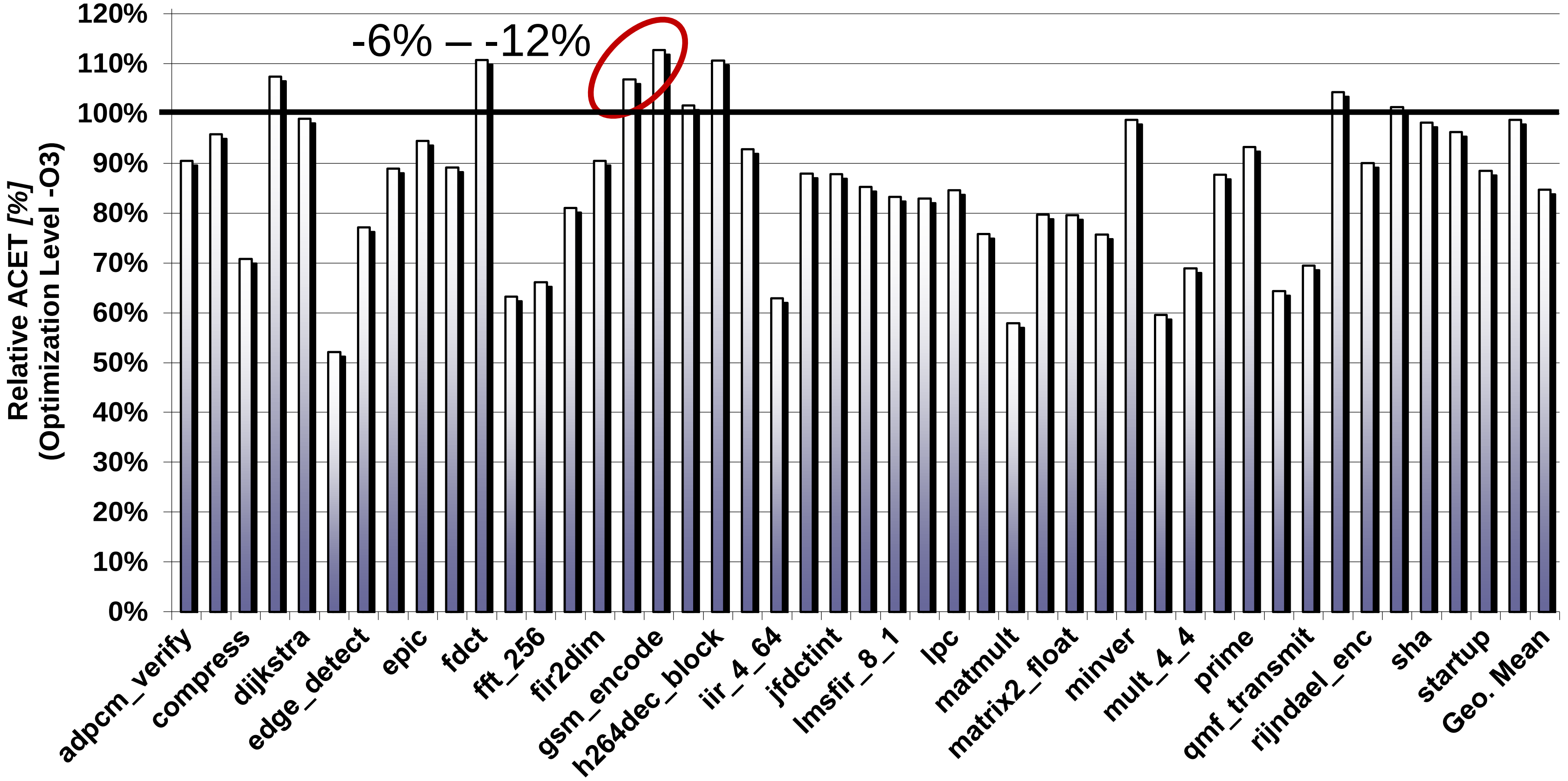
*[**H. Falk.** WCET-aware Register Allocation based on Graph Coloring. DAC, San Francisco, 2009]*

# Relative $WCET_{EST}$ after WCET-aware Graph Coloring




100% = $WCET_{EST}$ using Standard Graph Coloring (highest degree)

# Relative ACET after WCET-aware Graph Coloring




100% = ACET using Standard Graph Coloring (highest degree)

# Discussion

- $WCET_{EST}$ reductions from 6.9% up to 75.9%, on average 33.9%.
- Allocation of all 46 benchmarks: total of 1,979 WCET analyses.
- Run-time of WCET graph coloring: 12:15 hours for all 46 benchmarks
  ☞ 16 minutes per benchmark on average
- ACET reductions of up to 47.9%, but decreases of up to 12.7%. On average, 15.2% ACET reduction.
- Benchmarks behave very different w.r.t. $WCET_{EST}$ and ACET:
  **`gsm`** family: 51.5% – 66.2% $WCET_{EST}$ reduction
  6.8% – 12.7% ACET degradation
- *Reason:* WCET graph coloring avoids spilling along WCEP but inserts spill code at other places in the CFG which are frequently executed in an average-case scenario.

# Conclusions

**Comparison with Consequences for $\text{WCET}_{\text{EST}}$ Optimizations**

WCET-aware optimizations...

– ... mandatorily need detailed knowledge of the WCEP

👍 *WCET graph coloring considers the WCEP*

– ... always have to be aware that the WCEP can change after each individual optimization decision

👍 *WCET graph coloring updates the WCEP after each modification of the code*

– ... should take the decision where to optimize something not only based on local information, but should always consider the global effects of an optimization decision

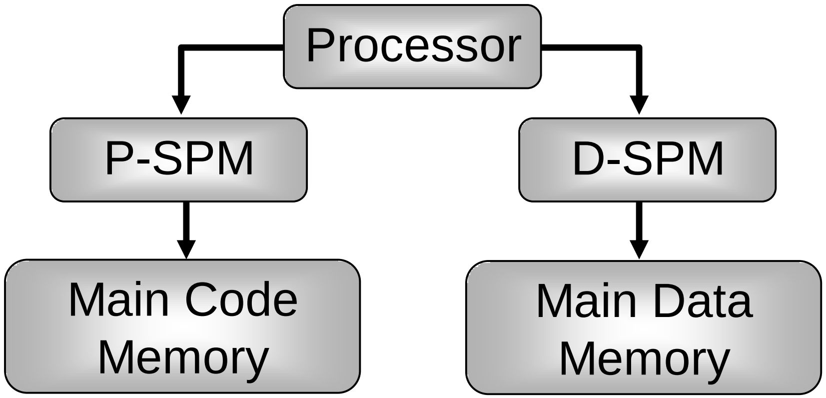
👎 *WCET graph coloring is greedy heuristic that is driven solely by local data per basic block*

# Chapter Contents

## 9. WCET-Aware Compilation

- Introduction
  - Integration of a WCET Timing Model into a Compiler
  - Challenges for WCET-Aware Optimization
- Procedure Cloning & Positioning
  - WCET-Aware Procedure Cloning
  - Procedure Positioning for Cache Miss Reduction
- Register Allocation
  - Problem of Classical Graph Coloring
  - WCET-Aware Graph Coloring
- Scratchpad Allocation of Data and Code
  - Allocation of global Data
  - Allocation of Basic Blocks

# In the Following: Harvard Architectures




- Separate busses and memories for code and data
- Scratchpad allocation of code and data can be solved independently from each other

☞ Two separate ILPs for these optimizations

☞ Non-Harvard architectures with unified busses and memories for code and data: Straightforward combination of both ILPs

# ILP for WCET-aware SPM Allocation of Data

**Goal**

- Determine set of data objects (global variables or static local variables) to be allocated to the data SPM,
- such that selected data objects lead to overall minimization of $WCET_{EST}$
- under consideration of switching WCEPs.

**Approach**

- Integer-linear programming (ILP)

☞ Optimality of results

- *Notation:* Upper-case letters ≅ constants,
  lower-case letters ≅ variables

# Decision Variables & Costs

- ***Binary decision variables per data object:***

$$y_i = \begin{cases} 1 & \text{if data object } d_i \text{ is assigned to } mem_{spm} \\ 0 & \text{if data object } d_i \text{ is assigned to } mem_{main} \end{cases}$$

- ***Costs of basic block $b_j$:***

$$c_j = C_j - \sum_{d_i \in \text{data objects}} G_{i,j} * y_i$$

$c_j$ models the $\text{WCET}_{\text{EST}}$ of $b_j$, depending on whether the data objects accessed by $b_j$ are allocated to main memory or SPM, resp.
$C_j$: $b_j$'s $\text{WCET}_{\text{EST}}$ if all data objects reside in main memory
$G_{i,j}$: WCET reduction of $b_j$ if data object $d_i$ is assigned to SPM

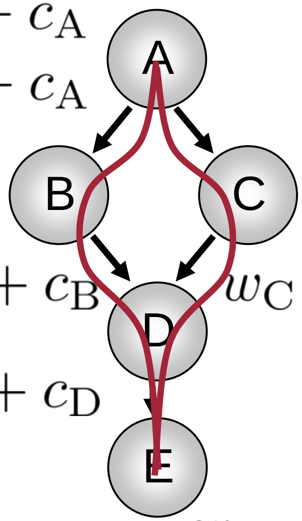
# Intraprocedural Control Flow (1)

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

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

<u>*Acyclic sub-graphs:*</u>

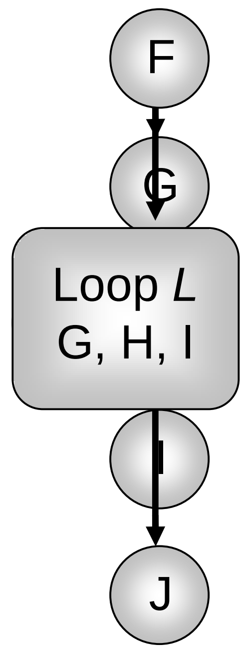
$$w_A \geq w_B + c_A$$
$$w_A \geq w_C + c_A$$




$$w_B \geq w_D + c_B \qquad w_C \geq w_D + c_C$$
$$w_D \geq w_E + c_D$$
$$w_E = c_E$$

$w_A$ = WCET of <u>*longest*</u> path starting at A

<u>*(Reducible) Loops:*</u>




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

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

# Intraprocedural Control Flow (2)

- ***Modeling of a function's control flow:***
  - For sink nodes $b_j$ of an acyclic sub-graph, $w_j$ is set to the costs $c_j$
  - For all other nodes $b_j$ of an acyclic sub-graph, the WCET of the paths starting in $b_j$ must be greater or equal than the WCET of each successor $b_{succ}$, PLUS the costs $c_j$ of $b_j$
  - For each successor $b_{succ}$ of $b_j$, one constraint is created in the ILP
  - ☞ Variable $w_j$ actually models all paths starting in $b_j$. Due to the ≥ operator in the inequations, the maximum over all paths starting in $w_j$ is modeled
  - 👍 Potential changes of the WCEP from one successor $b_{succ1}$ to another successor $b_{succ2}$ of $b_j$ are considered by construction

# Intraprocedural Control Flow (3)

- ***Modeling of a function's control flow:***
  - Reducible loops *L* have exactly one entry basic block $b^L_{entry}$
  - By "ignoring" of the back-edge of a reducible loop *L*, the CFG of the loop body becomes acyclic
  - Create constraints for acyclic loop body as shown on slide 65 (left part)
  - ☞ Variable $w^L_{entry}$ models $WCET_{EST}$ of the entire body of loop *L* if it is executed *exactly once*
  - Multiplication of $w^L_{entry}$ by the maximal number $C^L_{max}$ of iterations of *L* provides $WCET_{EST}$ for *all executions* of the loop
  - ☞ Costs of *L* are equal to the $WCET_{EST}$ of *L* for all executions

# Interprocedural Control Flow

- ***Modeling function calls:***
  - Each function $F$ has dedicated entry BB $b^F_{entry}$
  - Variable $w^F_{entry}$ models $\text{WCET}_{\text{EST}}$ of the longest path in $F$ that starts in $b^F_{entry}$
  - ☞ $w^F_{entry}$ models $\text{WCET}_{\text{EST}}$ of $F$ for exactly 1 execution of $F$
  - ☞ If $F'$ calls function $F$: Add $w^F_{entry}$ to $\text{WCET}_{\text{EST}}$ of $F'$

- ***Function calls in basic block $b_j$:***
  - "Call penalty" for calling basic block:

$$cp_j = \begin{cases} w^F_{entry} & \text{if } b_j \text{ calls } F \\ 0 & \text{else} \end{cases}$$

  - ILP constraint per basic block:

$$\forall (b_j, b_{succ}) : w_j \geq w_{succ} + c_j + cp_j$$

# Scratchpad Capacity and Objective Function

- ***Scratchpad capacity constraint:***

$$\sum_{d_i \in \text{data objects}} (S_i * y_i) \leq S_{spm}$$

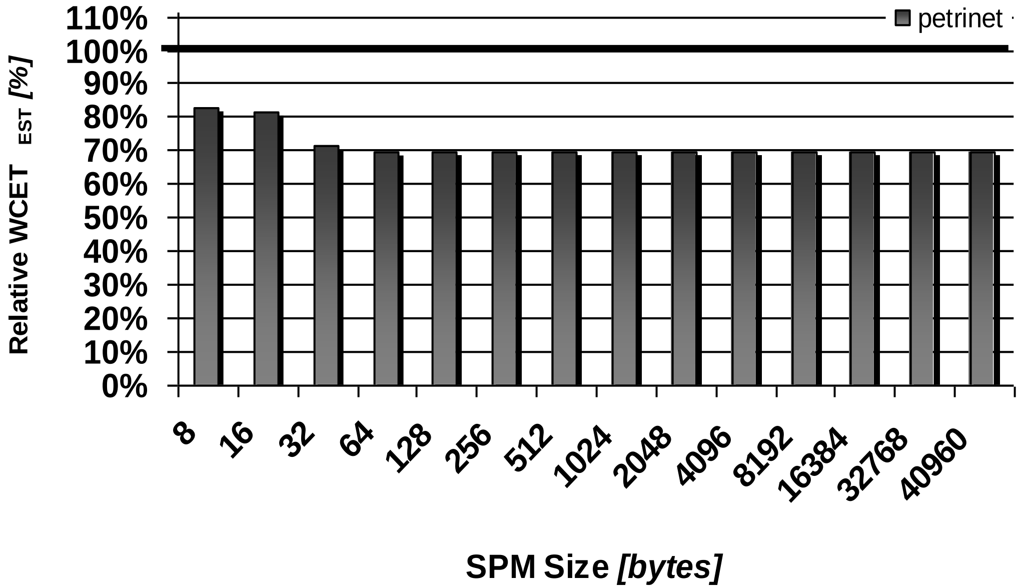
The sum of the sizes of all data objects allocated onto the SPM is less than or equal to the totally available SPM capacity.

- ***Objective function:***
  - $w^F_{entry}$ models $\text{WCET}_{\text{EST}}$ of $F$ if $F$ is executed exactly once
  - Variable $w^{\texttt{main}}_{entry}$ models $\text{WCET}_{\text{EST}}$ of the entire program

☞ $w^{\texttt{main}}_{entry} \rightsquigarrow min.$

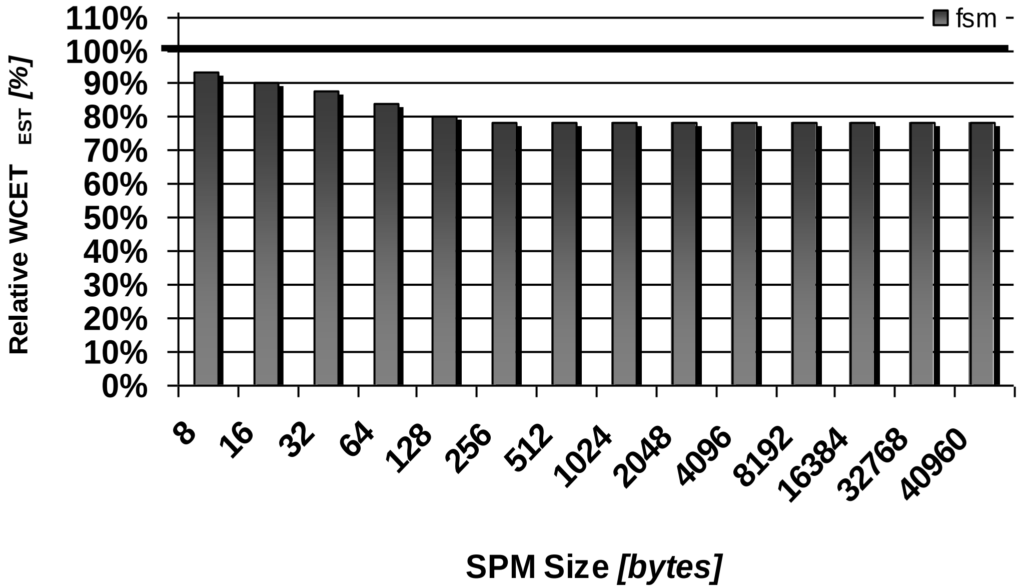
*[**F. Rotthowe.** Scratchpad Allocation of Data for Worst-Case Execution Time Minimization (in German). Diploma Thesis, TU Dortmund, 2008]*

# Rel. $WCET_{EST}$ after D-SPM Allocation of `petrinet`



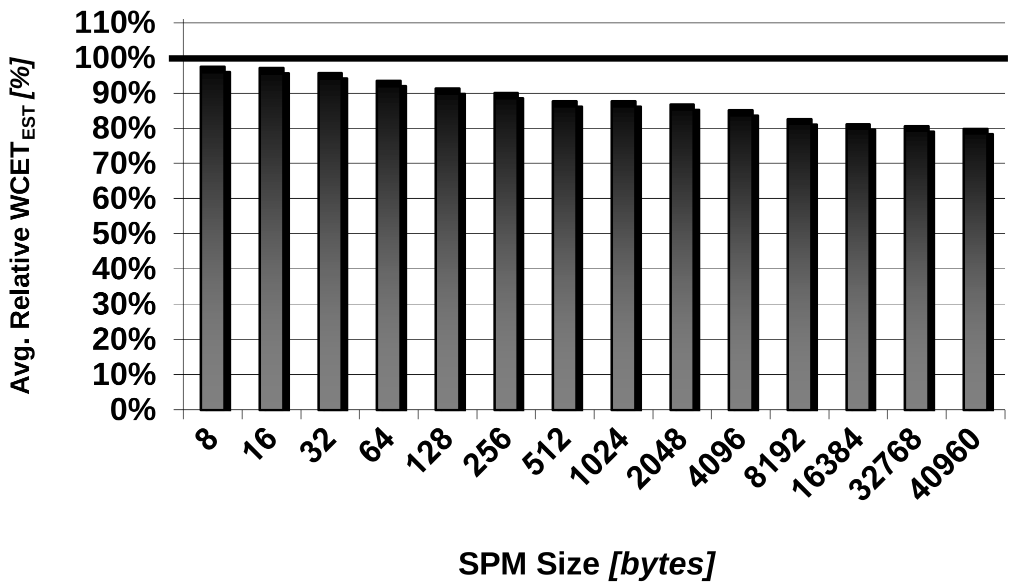

- Notable $WCET_{EST}$ reductions already for SPMs of only a few bytes
- 6 global variables of 72 bytes size in total
- $WCET_{EST}$ reductions by 28.6% for 32 bytes SPM
- X-Axis: Absolute SPM sizes
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# Rel. $WCET_{EST}$ after D-SPM Allocation of `fsm`




- More steady $WCET_{EST}$ reductions for increasing SPM sizes
- 98 global variables à 4 bytes size each
- $WCET_{EST}$ reductions by 21.4% for 256 bytes SPM
- X-Axis: Absolute SPM sizes
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# Rel. $WCET_{EST}$ after D-SPM Allocation of 14 Benchmarks




- Steady $WCET_{EST}$ reductions for increasing SPM sizes
- $WCET_{EST}$ reductions from 2.7% – 20.6%
- X-Axis: Absolute SPM sizes
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# 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

- *Notation:* Upper-case letters ≅ constants,
  lower-case letters ≅ variables

# Decision Variables & Costs

– ***Binary decision variables per basic block:***

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

– ***Costs of basic block $b_i$:***

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

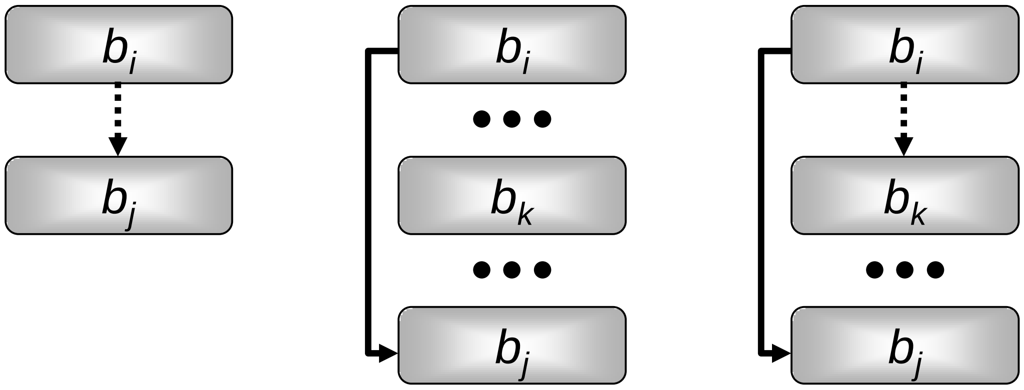
$c_i$ models the $\text{WCET}_{\text{EST}}$ of $b_i$ if it is allocated to main memory or SPM, resp.

– ***Modeling of the intraprocedural control flow:***
As before in the WCET-aware SPM allocation of data

# Cross-Memory Jumps

- ***Allocation of consecutive basic blocks:***
  - Allocation of consecutive basic blocks in the CFG to different memories requires adaption/insertion of dedicated jumping code
  - Cross-memory jumps are costly: Often need more than 1 instruction
  - Jumping code: *Variable* overhead in terms of $WCET_{EST}$ and code size, depending on decision variables *(☞ cf. chapter 7)*

- ***Jump Scenarios:***



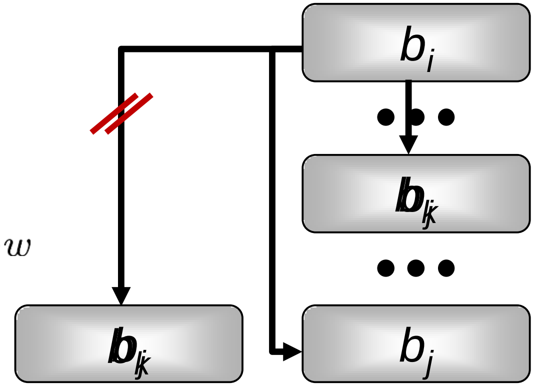

***a) Implicit*** ***b) Unconditional*** ***c) Conditional***

# Penalties for Cross-Memory Jumps

- ***Jump Penalty (⊗ ≅ Boolean XOR):***
  - *<u>Penalty for implicit jumps:</u>* $jp^i_{impl}$

    $$jp^i_{impl} = (x_i \otimes x_j) * P_{high}$$

    High penalty if basic blocks *i* and *j* are placed in different memories
  - *<u>Penalty for unconditional jumps:</u>* $jp^i_{uncond}$
    - If $b_i$ and $b_j$ in different memories: $P_{high}$
    - If $b_i$ and $b_j$ adjacent in same memory: 0
    - If $b_i$ and $b_j$ not adjacent in same memory: $P_{low}$




$$jp^i_{uncond} = (x_i \otimes x_j) * P_{high} + \overline{(x_i \otimes x_j)} * (1 - \prod_{b_k \in \text{JS b)}} (x_i \otimes x_k)) * P_{low}$$

  - *<u>Conditional jumps:</u>* Obvious combination of $jp^i_{impl}$ and $jp^i_{uncond}$

# Jump Penalties and Interprocedural Control Flow

– ***Jump penalties for basic block $b_i$:***

$$jp_i = \begin{cases} jp^i_{impl} & \text{if Jump Scenario of } b_i \text{ is } \mathit{implicit} \\ jp^i_{uncond} & \text{if Jump Scenario of } b_i \text{ is } \mathit{unconditional} \\ jp^i_{cond} & \text{if Jump Scenario of } b_i \text{ is } \mathit{conditional} \\ 0 & \text{else} \end{cases}$$

– ***Penalty for function calls for basic block $b_i$:***

$$cp_i = \begin{cases} w^F_{entry} + (x_i \otimes x^F_{entry}) * P_{high} & \text{if } b_i \text{ calls } F \\ \qquad +(1 - (x_i \otimes x^F_{entry})) * P_{low} & \\ 0 & \text{else} \end{cases}$$

If block $b_i$ calls function $F$: Add $\text{WCET}_{\text{EST}}$ of $F$ to $\text{WCET}_{\text{EST}}$ of $b_i$. Furthermore, add $P_{high}$ if function call is cross-memory call. If function call stays in the same memory, add only $P_{low}$.

# Sizes of Basic Blocks

- ***Constraint for all successors $b_{succ}$ of $b_i$:***

  $$\forall(b_i, b_{succ}) : w_i \geq w_{succ} + c_i + cp_i + jp_i$$

- ***Size of a basic block $b_i$:***
  - Size of $b_i$ depends on actual jumping code for $b_i$
  - Size of jumping code of $b_i$ depends on jump scenario:

  $$s_i = \begin{cases} (x_i \wedge \overline{x_j}) * S_{impl} & \text{if Jump Scenario of } b_i \text{ is } \mathit{implicit} \\ (x_i \wedge \overline{x_j}) * S_{uncond} & \text{if Jump Scenario of } b_i \text{ is } \mathit{unconditional} \\ (x_i \wedge \overline{x_k}) * S_{impl} + & \text{if Jump Scenario of } b_i \text{ is } \mathit{conditional} \\ \qquad (x_i \wedge \overline{x_j}) * S_{uncond} & \\ (x_i \wedge \overline{x^F_{entry}}) * S_{call} & \text{if } b_i \text{ calls } F \\ 0 & \text{else} \end{cases}$$

  - Total size of basic block $b_i$:
    Size $S_i$ of $b_i$ without any jumping code <u>*plus*</u>
    Size $s_i$ of $b_i$'s jumping code

# Scratchpad Capacity and Objective Function

- ***Scratchpad capacity constraint:***

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

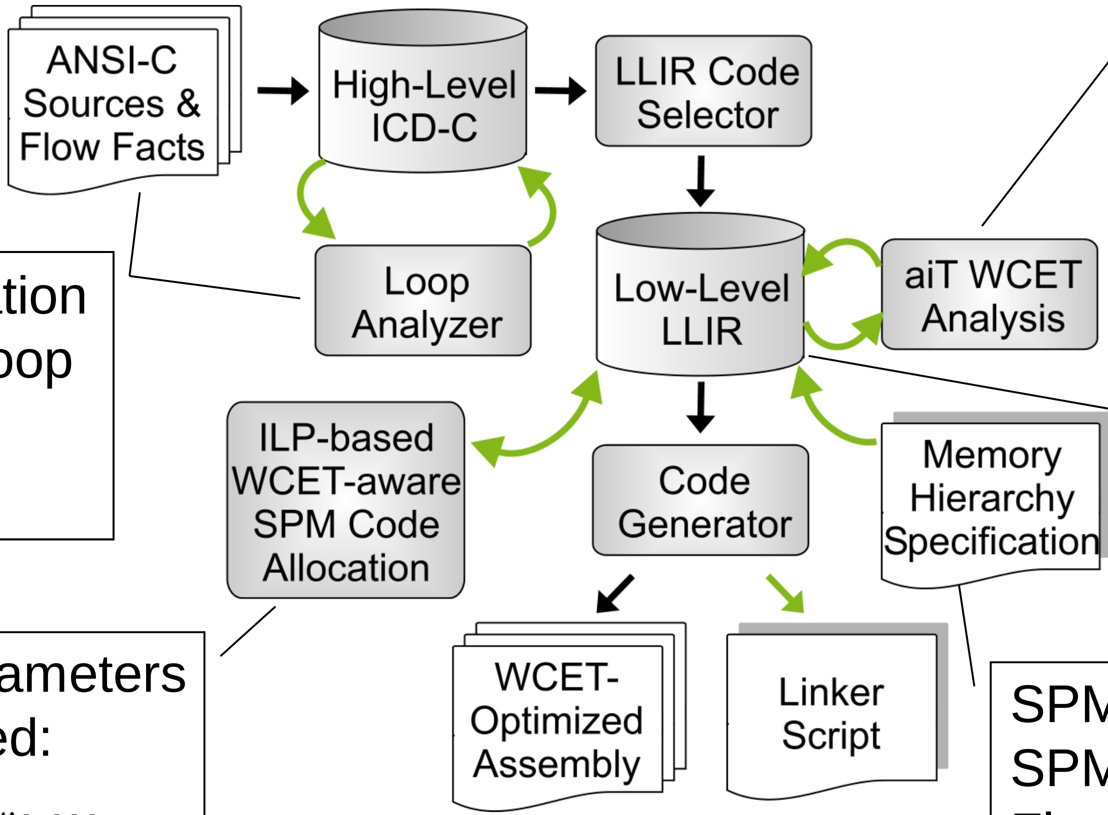
  The sum of the sizes of all basic blocks allocated onto the SPM without jumping code, plus the size of jumping code in $b_i$ is less than or equal to the totally available SPM capacity.

- ***Objective function:***

  $$w_{entry}^{\texttt{main}} \rightsquigarrow min.$$

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

# Determination of the Constants of the ILPs (1)




WCET$_{EST}$ of BB $b_i$ for SPM and main memory: $C^i_{main}$, $C^i_{spm}$

Max. iteration count of loop $L$: $C^L_{max}$

Size of BB $b_i$: $S_i$

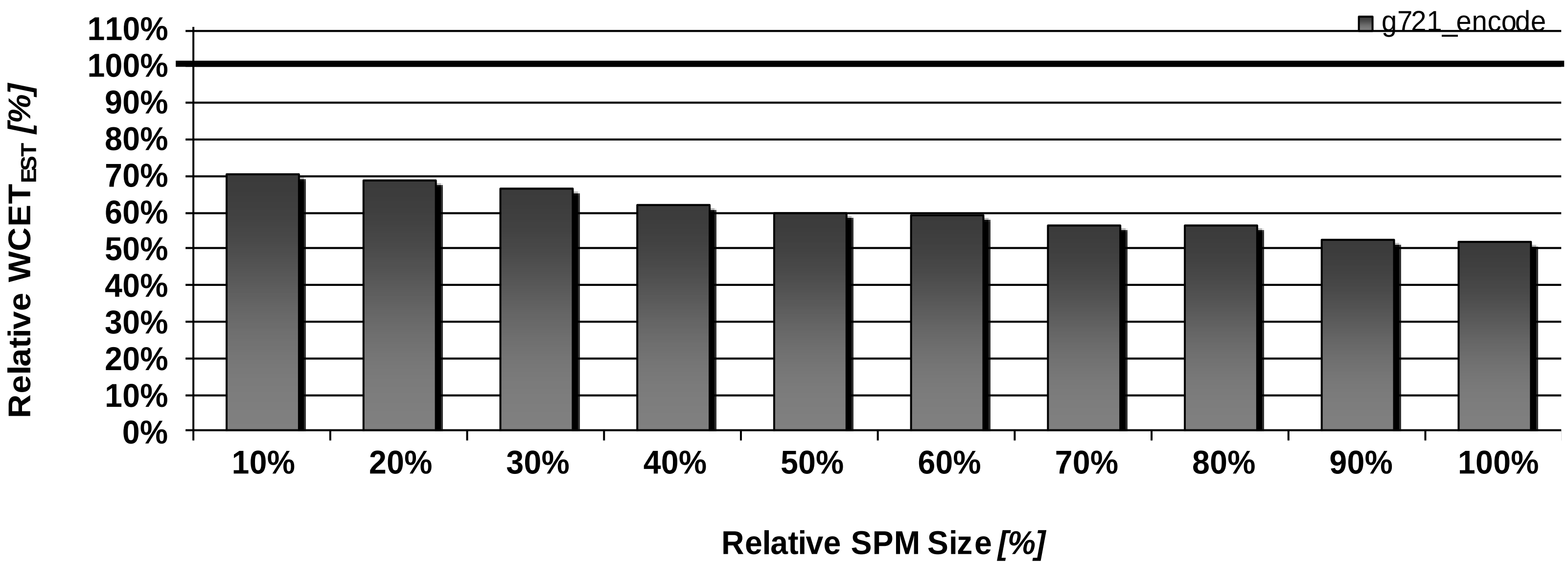
Other parameters hard-coded: $P_{high}, P_{low}, \ldots$

SPM size $S_{spm}$ = 47 kB
SPM access = 1 cycle
Flash access = 6 cycles

# Determination of the Constants of the ILPs (2)

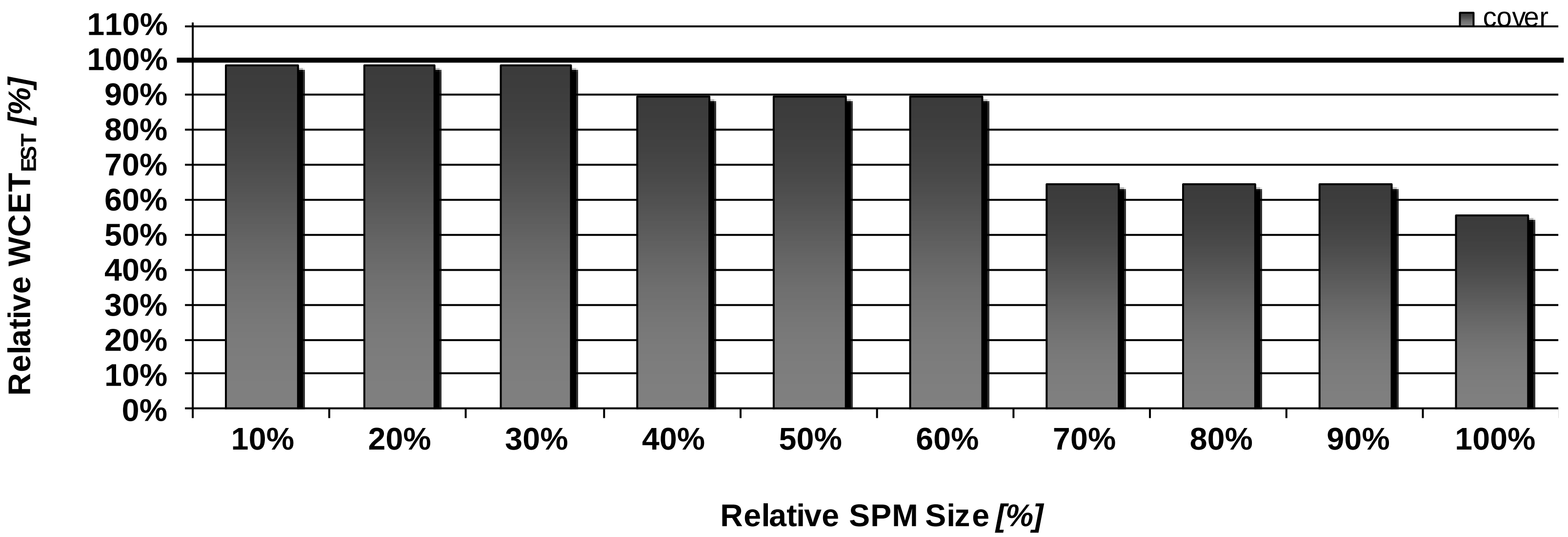
- *WCET$_{EST}$ $C^i_{main}$, $C^i_{spm}$ per basic block $b_i$ for both memories:*
  Determined by two WCET analyses, one in which all basic blocks lie in the SPM, one with all blocks in main memory.
- *Max. iteration count of loops $C^L_{max}$:*
  Either annotated in the source code using flow facts, or determined by WCC's automatic loop bound analysis.
- *Size $S_i$ of a basic block without jumping code:*
  By simple enumeration of all LIR operations
- *Size $S_{spm}$ of the scratchpad:*
  Taken from WCC's memory hierarchy specifications
- *Remaining parameters determined experimentally:*
  $P_{high}$ = 16 $P_{low}$ = 8
  $S_{impl}$ = $S_{uncond}$ = 10 $S_{call}$ = 12

# Rel. $WCET_{EST}$ after P-SPM Allocation of `g721_encode`



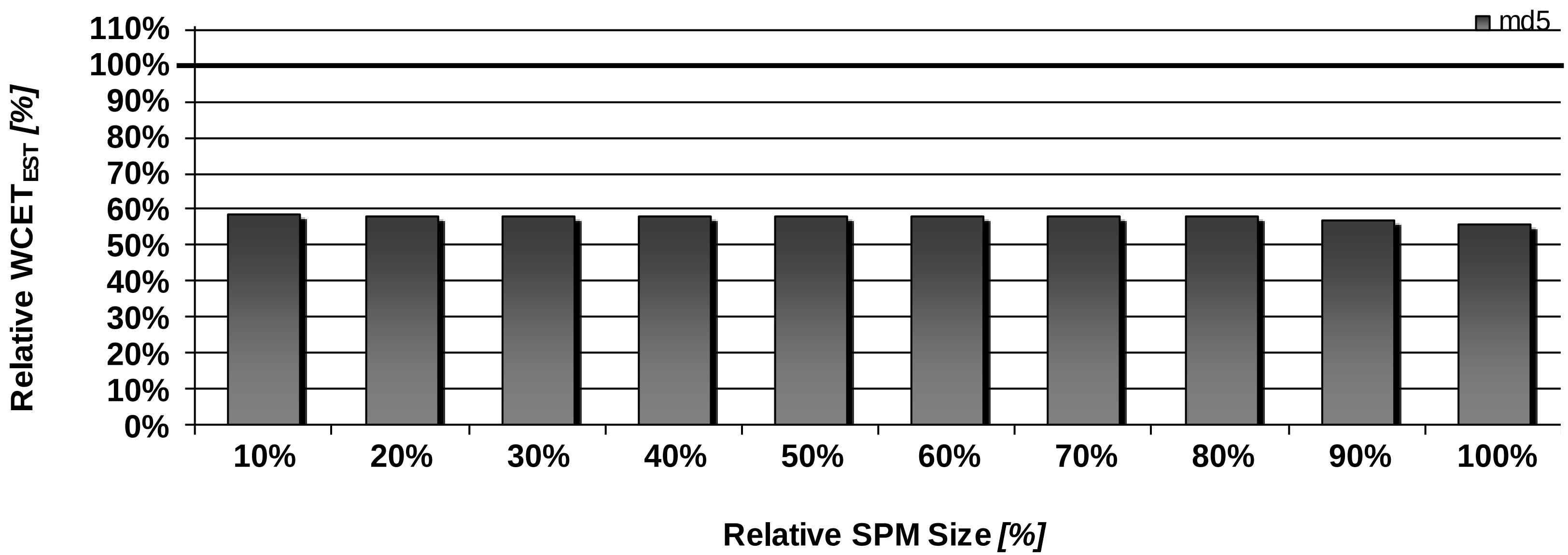

- Steady $WCET_{EST}$ decreases for increasing SPM sizes
- $WCET_{EST}$ reductions from 29% – 48%
- X-Axis: SPM size = *x*% of benchmark's code size
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# Rel. $WCET_{EST}$ after P-SPM Allocation of `cover`




- Stepwise $WCET_{EST}$ decreases: Useful content allocated to SPM only at 40%, 70% and 100% relative SPM size
- $WCET_{EST}$ reductions of 10%, 35% and 44%
- X-Axis: SPM size = *x*% of benchmark's code size
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

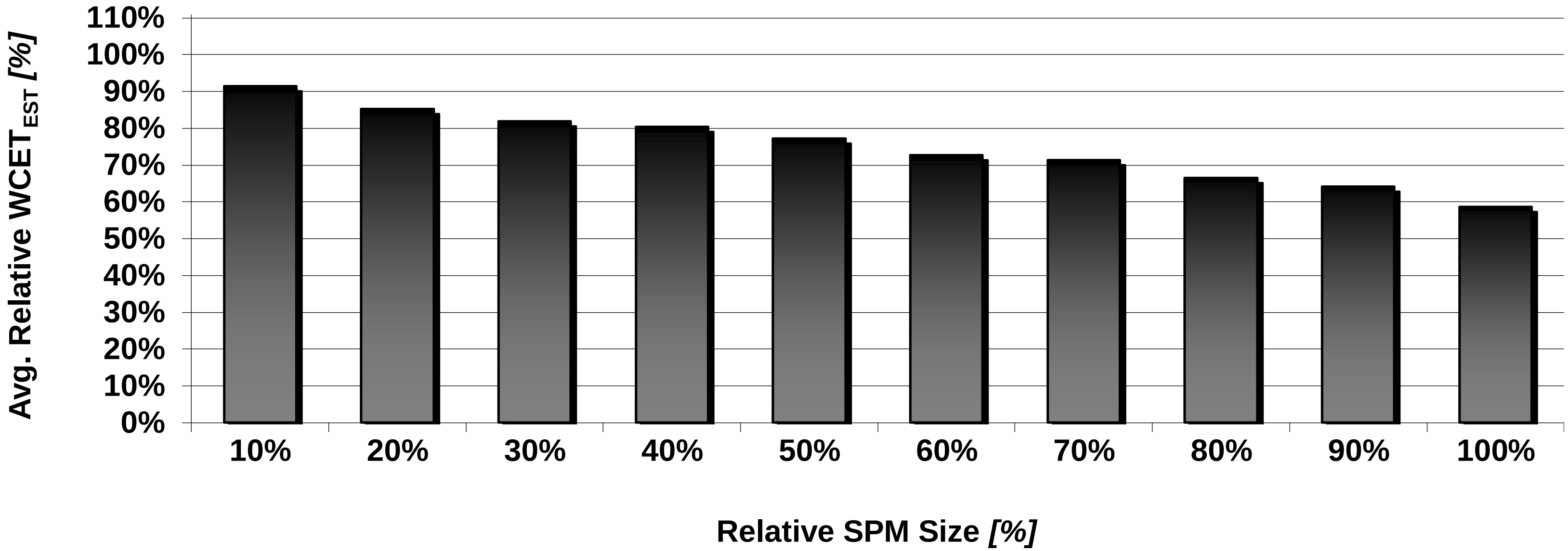
# Rel. $WCET_{EST}$ after P-SPM Allocation of `md5`




- Almost invariable $WCET_{EST}$ reductions for all SPM sizes: 40% - 44%
- ILP clearly finds tiny but time-critical hot-spot of **`md5`** and allocates it to SPM

- X-Axis: SPM size = *x*% of benchmark’s code size
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# Rel. $WCET_{EST}$ after P-SPM Allocation of 73 Benchmarks




- Steady $WCET_{EST}$ reductions for increasing SPM sizes
- $WCET_{EST}$ reductions from 8% – 41%

- X-Axis: SPM size = *x*% of benchmark's code size
- Y-Axis: 100% = $WCET_{EST}$ when not using SPM at all

# Conclusions

**Comparison with Consequences for $\text{WCET}_{\text{EST}}$ Optimizations**

WCET-aware optimizations...

– ... mandatorily need detailed knowledge of the WCEP

👍 *SPM allocations consider the WCEP*

– ... always have to be aware that the WCEP can change after each individual optimization decision

👍 *SPM allocations inherently capture WCEP changes inside the ILP*

– ... should take the decision where to optimize something not only based on local information, but should always consider the global effects of an optimization decision

👍 *Objective functions of the ILPs model the global WCET of a program that is subject to minimization.*

# References

**WCC Compiler Infrastructure**

– H. Falk, P. Lokuciejewski. *A compiler framework for the reduction of worst-case execution times*. Springer Real-Time Systems 46(2), October 2010.

# Summary

**Compilers for $\text{WCET}_{\text{EST}}$ Minimization**

– Integration of a formal WCET timing model into compiler
– Challenge: To consider unstable WCEPs in the course of optimizations

**WCET-aware Optimizations**

– Procedure Cloning & Positioning: Greedy heuristics that determine current WCEP via repeated WCET analyses
– Register allocation: cyclic dependencies between register allocation and WCET analysis; graph coloring along the always current WCEP
– Scratchpad allocations: Inherent modelling of WCEP in the ILPs; eliminates need for repeated WCET analyses during optimization