# Software Pipelining and Register Pressure in VLIW Architectures: Preconditionning Data Dependence Graphs is Experimentally Better than Lifetime-Sensitive Scheduling

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# An old debate about an open question

- Phase ordering problem:
  instruction scheduling before/after register allocation?
- Highlighted in the 80's for sequential code, with register minimisation
- Wealth of heuristics for acyclic scheduling
- What about cyclic scheduling?

# Related work

- Software pipelining under resource constraints only
  $\longrightarrow$ register pressure often goes out of control
- Software pipelining under resource and register constraints
  $\longrightarrow$ to spill or to increase the $\mathbf{II}$ – that is the question
- Post-pass cyclic register allocation
  $\longrightarrow$ necessary: modulo expansion (unrolling) and register assignment

# Our strategy for VLIW

1. Decoupling register pressure control from instruction scheduling
   $\longrightarrow$ better compiler engineering
   $\longrightarrow$ focus scheduling on the core objectives (**II**, hiding memory latency)

2. Handling register constraints before scheduled resource constraints
   $\longrightarrow$ Memory operations have unknown static latencies $\longrightarrow$ Imprecise scheduling and WCET analysis

3. Avoid spilling instead of scheduling spill code while taking care of **II**
   $\longrightarrow$ Memory operations consume more power

# The target platform

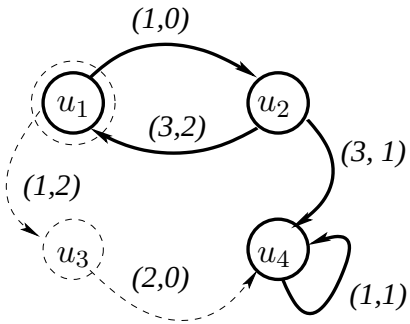
## ST231 processor

- 4-issue VLIW processor at 400 MHz
- 64 general purpose 32-bit registers (GR)
- 8 1-bit condition registers (BR)
- 1 LSU, 1 BCU, 4 ALU and 1 MAU functional units
- 32 KB 4-way Dcache, 32 KB direct-mapped Icache

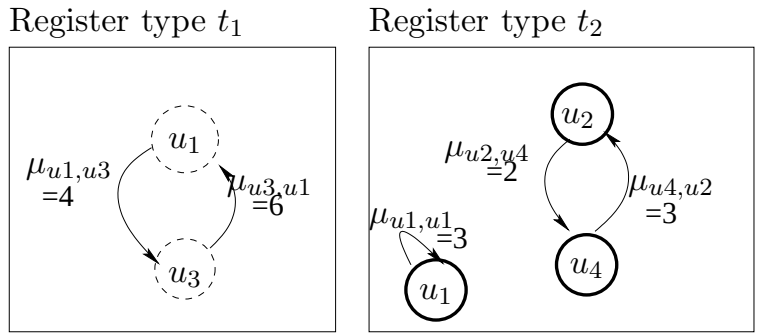
## Toolchain: ST200cc with LAO

- Front-end compiler based on Open64
- At -O3 optimization level, the LAO backend component performs VLIW software pipelining
- Post-pass register allocation in ST200cc

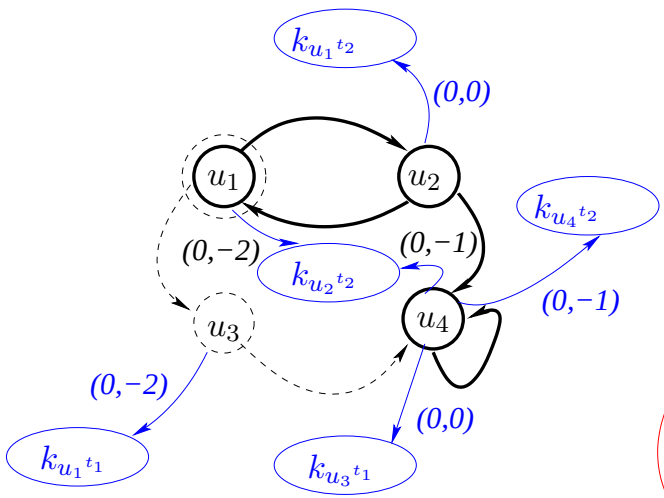
# SIRA: an example




(a) Initial DDG



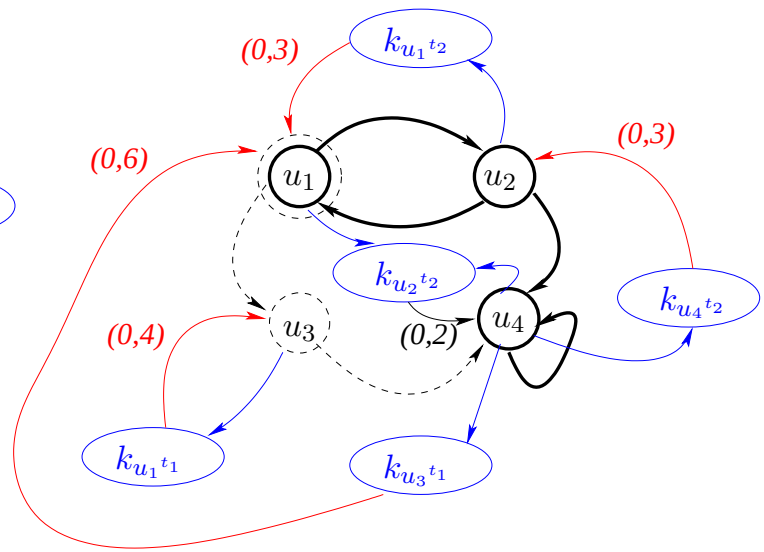

(b) Reuse Graphs for Register Types t1 and t2




(c) DDG with Killing Nodes

$V^k = \{k_{u^t} | u \in V^{R,t}\}$

$E^k = \{(v, k_{u^t}) | v \in Cons(u^t)\}$




(d) Preconditioned DDG after Applying SIRA

$E^{\mu} = \{(k_{u^t}, v) | (u, v) \in E^{\text{reuse},t}\}$

# Comparing SIRA vs. existing work

- Unique features of SIRA
  - Optimise for multiple register types simultaneously or one after another
  - Model (read and write) delays in accessing registers
  - Model register banks, buffers or rotating register files.
  - Register pressure guarantee independent of the scheduling algorithm
  - Correctness proofs for the model and algorithms
  - Reproducible results: standalone C library (`SIRAlib`), distributed with experimental data
- Validation of the effectiveness of SIRA in a production compiler
  - Compiler construction: simplifies scheduling/allocation ordering
  - Software engineering: SIRA as an independent C library plugable in any compiler
  - Reproducibility: the source code is publicly released (LGPL)
  - Effectiveness: already published for standalone DDG, experimental results of this talk for an integrated context.

# SIRA: schedule independent register allocation

**Fundamental principle: Theorem [Touati2001]**

Let $\mathbf{G}$ be a loop DDG. Let $\mathbf{G'}$ the extended DDG of $\mathbf{G}$ associated with the valid reuse graph $\mathbf{G}^{\mathrm{reuse},\mathbf{t}}$ for the register type $\mathbf{t}$. Then, any software pipelining $\boldsymbol{\sigma}$ of $\mathbf{G}$ does not require more then $\sum \boldsymbol{\mu}^{\mathbf{t}}_{\mathbf{u},\mathbf{v}}$ registers of type $\mathbf{t}$, where $\boldsymbol{\mu}^{\mathbf{t}}_{\mathbf{u},\mathbf{v}}$ is the reuse distance between $\mathbf{u}$ and $\mathbf{v}$ in $\mathbf{G}^{\mathrm{reuse},\mathbf{t}}$. Formally:

$$\forall \boldsymbol{\sigma} \in \boldsymbol{\Sigma}(\mathbf{G}), \mathrm{PeriodicRegisterRequirement}^{\mathbf{t}}_{\boldsymbol{\sigma}}(\mathbf{G}) \leq \sum \boldsymbol{\mu}^{\mathbf{t}}_{\mathbf{u},\mathbf{v}}$$

# SIRA: How it works ?

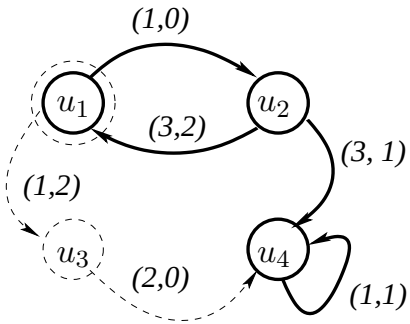
The SIRALINA heuristic works in two polynomial steps:

1. Step 1: Computes the minimal reuse distances between every possible couple of statements (*i.e.* Compute a function $\overline{\widehat{\mu^{\mathbf{t}}}} : \mathbf{V}^{\mathbf{R},\mathbf{t}} \times \mathbf{V}^{\mathbf{R},\mathbf{t}} \longrightarrow \mathbb{Z}$ for each register type $\mathbf{t}$);
2. Step 2: Compute a bijection $\mathbf{E}^{\mathrm{reuse},\mathbf{t}} : \mathbf{V}^{\mathbf{R},\mathbf{t}} \longrightarrow \mathbf{V}^{\mathbf{R},\mathbf{t}}$ that minimises $\sum_{\mathbf{e_r} \in \mathbf{E}^{\mathrm{reuse},\mathbf{t}}} \overline{\widehat{\mu^{\mathbf{t}}}}(\mathbf{e_r})$ for each register type $\mathbf{t}$.

# SIRA: How it works ?

1. Step 1: It is a cyclic scheduling problem under precendence constraints only. It may be solved optimally by a min-cost max flow problem, or by a linear program with a totally unimodular constraints matrix. The complexity is $\mathbf{O(\|V\|^3 \log \|V\|)}$
2. Step 2: It is a linear assignment problem, solved optimally by the Hungarian algorithm in $\mathbf{O(\|V\|^3)}$.

# SIRA: How it works ?

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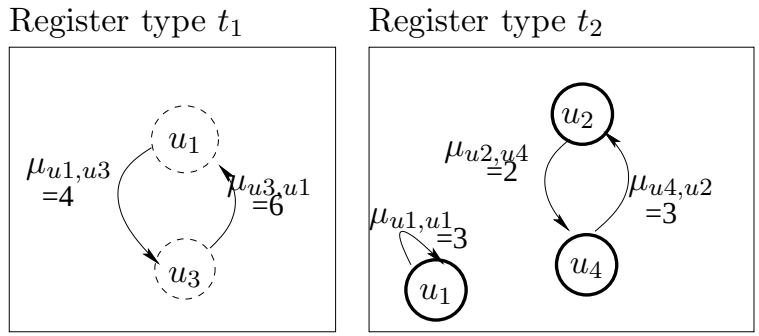


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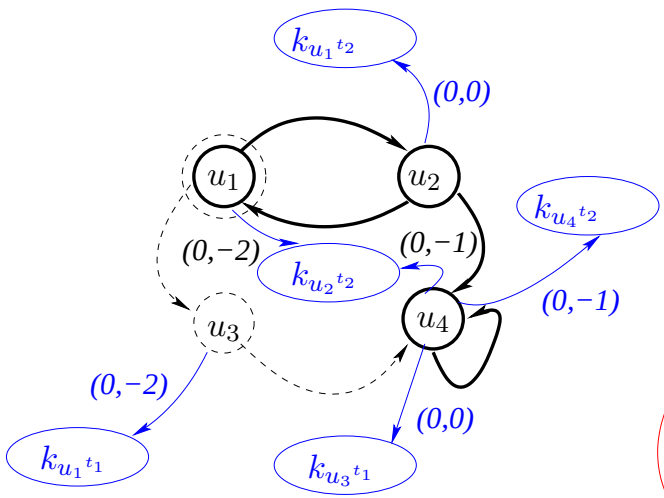


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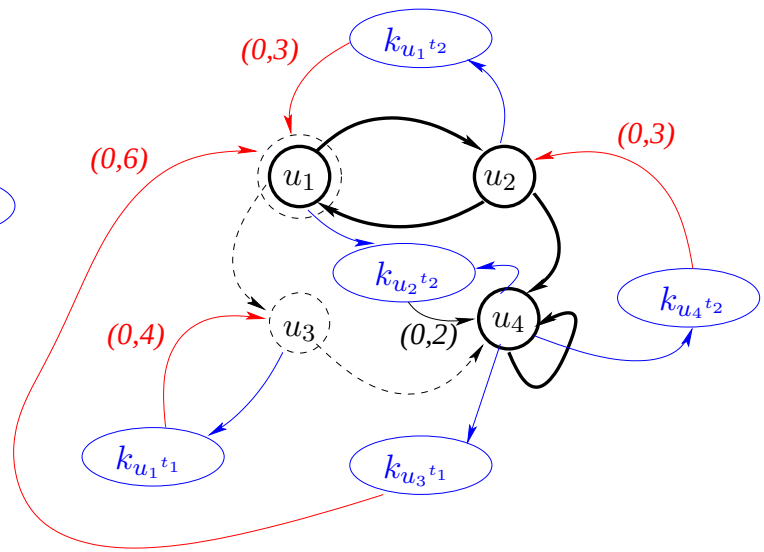


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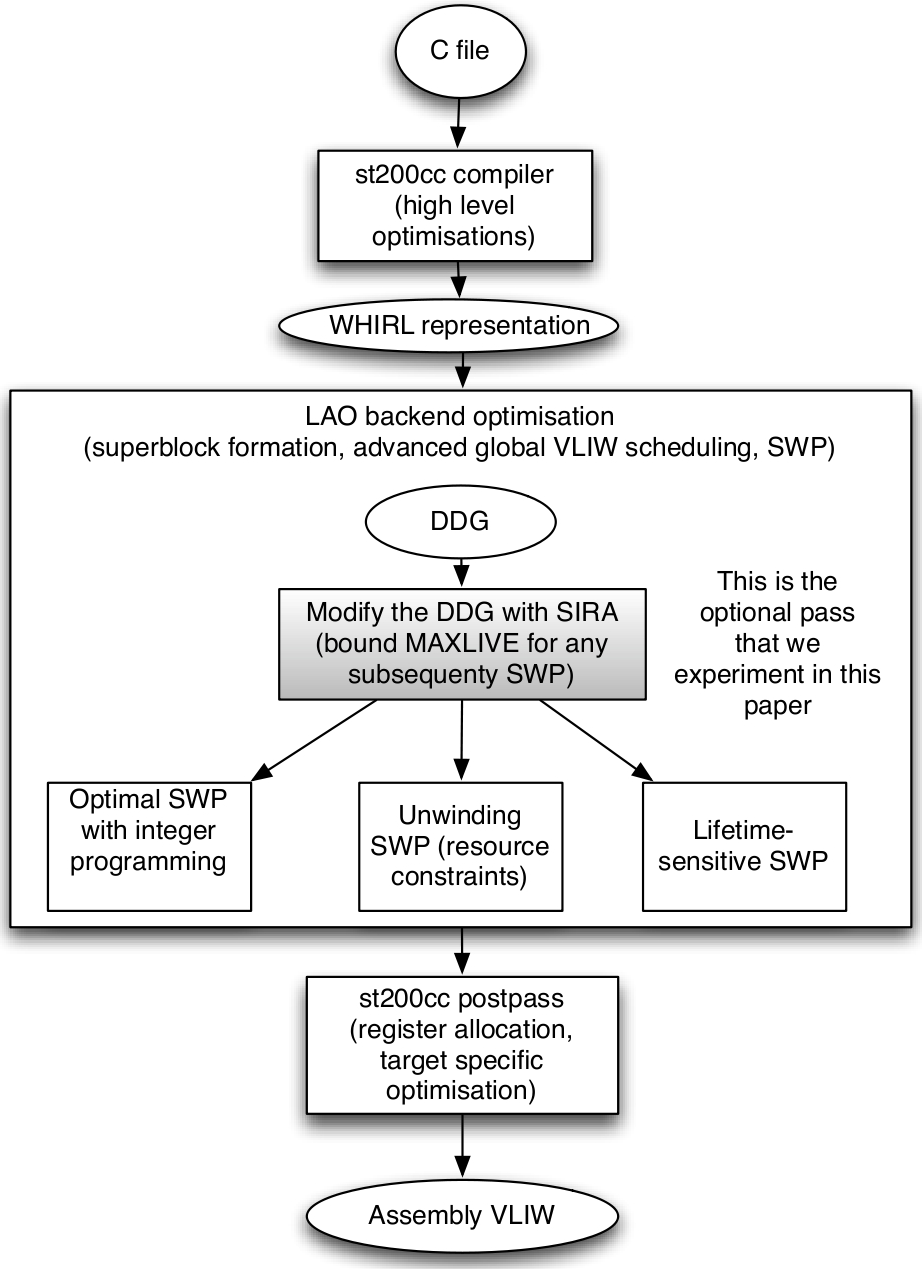
# Plugging SIRA into the ST231 toolchain



# Experiments

## Setup

- FFMPEG, MEDIABENCH and SPEC CPU2000 benchmarks
- ST231 register count lowered to 32 GR, 4 BR, optimized simultaneously

## Instruction schedulers

- SIRA frees aggressive scheduling from register pressure worries
  1. Optimal: Integer Linear Programming, minimize **II** and schedule length
  2. Unwinding heuristic: unrolling-based method to build modulo schedules
  3. Lifetime-sensitive heuristic: minimizes the sum of life-ranges

## Questions

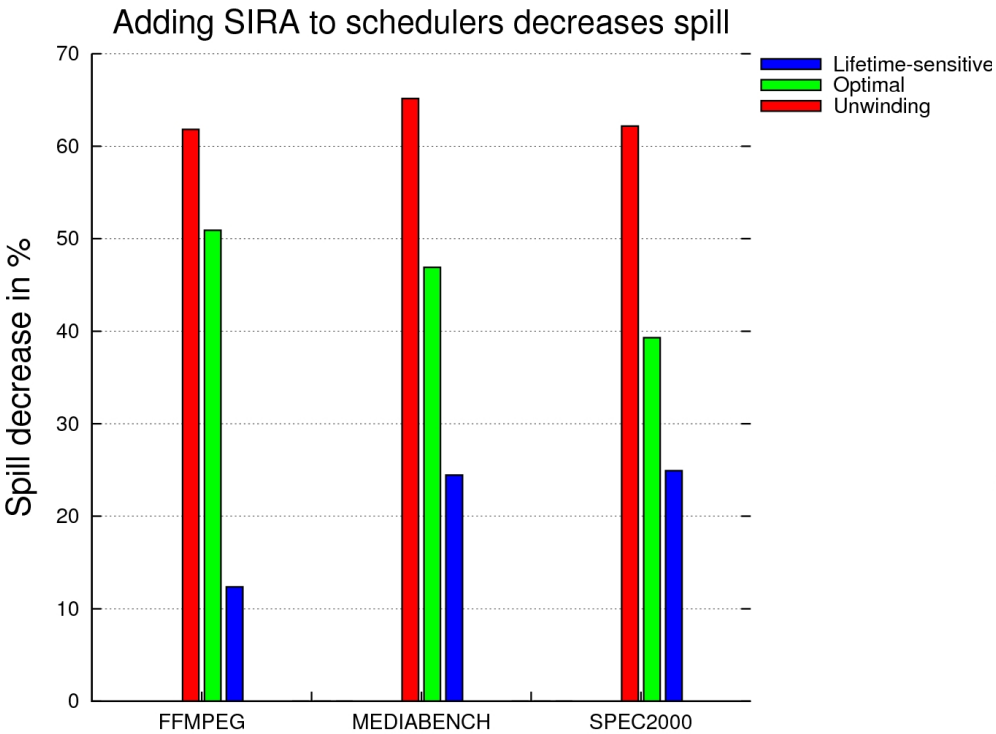
- Does SIRA improve performance? For which scheduler?
- How does a lifetime sensitive heuristic compare with the combination of SIRA with a pressure-unaware algorithm?

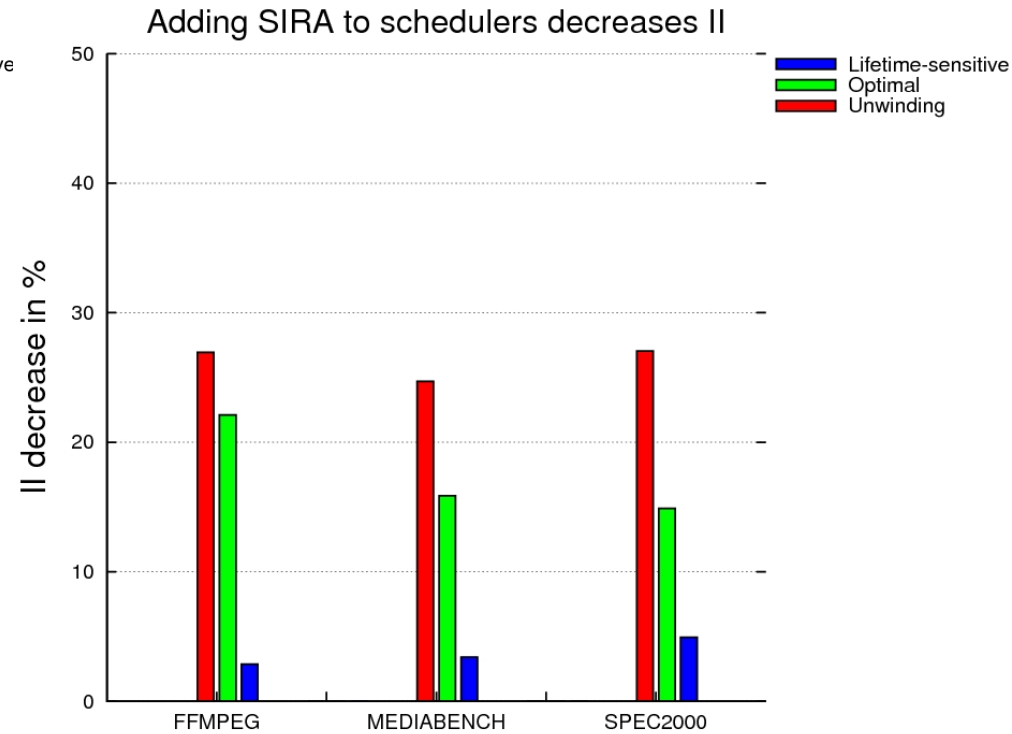
# Experiments

## Setup

- Instrumentation of the toolchain yields static numbers about spills and **II**
- For each benchmark and each scheduler, we compare the numbers obtained with the scheduler alone to those obtained with both SIRA and the scheduler

# Experiments




- Mean spill variation $= \frac{\sum (\mathbf{Spill_{with\_SIRA}} - \mathbf{Spill_{without\_SIRA}})}{\sum \mathbf{Spill_{without\_sira}}}$
- Mean **II** variation $= \frac{(\sum \mathbf{II_{with\_SIRA}} - \mathbf{II_{without\_SIRA}})}{\sum \mathbf{II_{without\_SIRA}}}$

# Experiments: cross-comparison

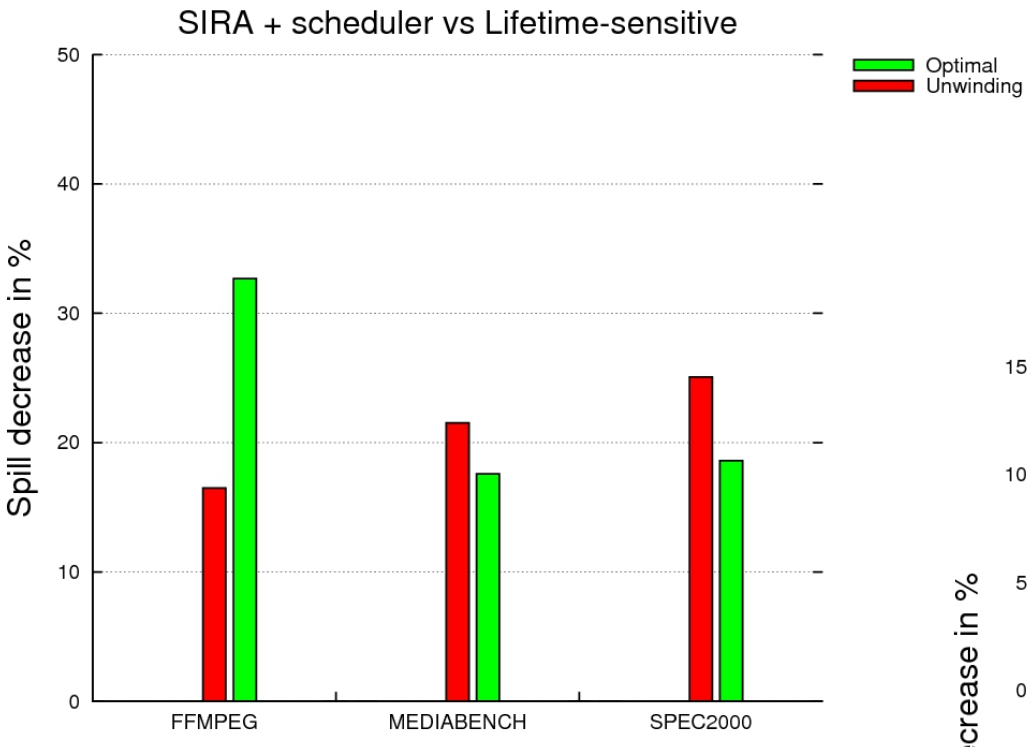
**Question**

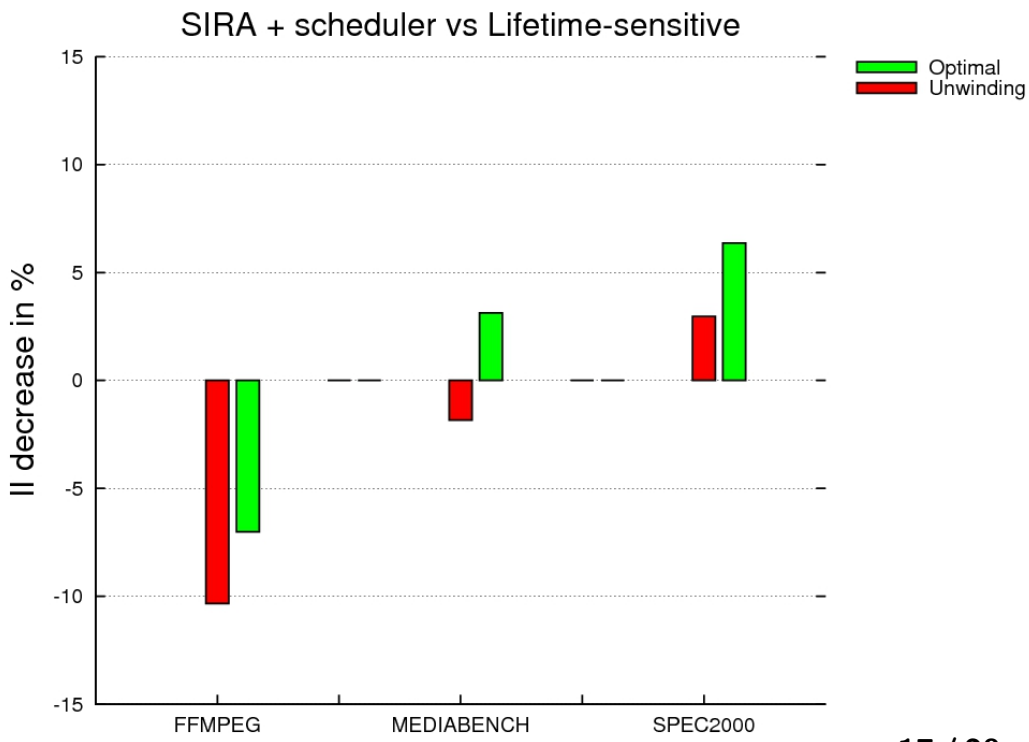
How does a lifetime sensitive heuristic compare with the combination of SIRA with a pressure-unaware algorithm?

**Setup**

- SIRA + unwinding scheduler vs. lifetime-sensitive scheduler alone
- SIRA + optimal scheduler vs. lifetime-sensitive scheduler alone

# Experiments: cross-comparisons

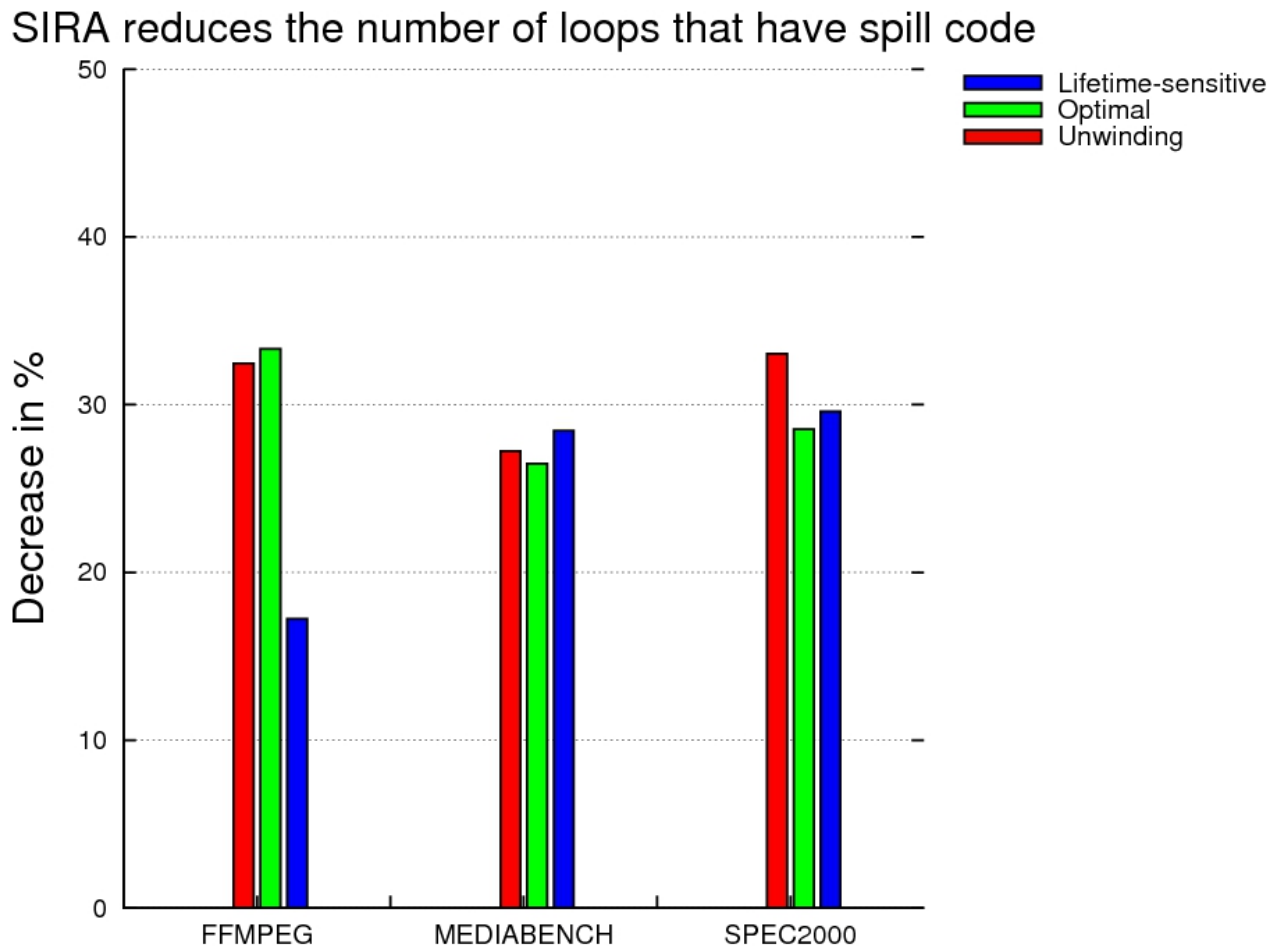


# Experiments: spill code in post-pass

Does SIRA reduce spill or prevent it altogether?

Answer: evaluate $\frac{\textbf{Loops\_that\_do\_not\_have\_spill\_anymore\_once\_SIRA\_is\_used}}{\textbf{Loops\_that\_had\_spill\_without\_SIRA}}$



# Conclusions

- Using SIRA significantly decreases both **II** and spills, for all schedulers
- Not surprisingly, results are less impressive on the lifetime-sensitive scheduler, since the heuristic already reduce register pressure
- The combination of SIRA with an aggressive scheduler outperforms the lifetime-sensitive approach

# The speedup debate

- Speedups depend on the data input, and the time fraction spend in the SWP loops.
- The compiler optimises for an architectural objective, while speedup comes from a complex interaction with the micro-architecture and the experimental environment.
- If you get a speedup, who guarantees that it comes as a direct consequence of the plugged optimisation ? Phase ordering, hidden side effects, etc.
- In our case: SWP loops account for 0% to 5% of the whole applicatiosn execution times. Most of the speedups are equal to 1.
- The other speedups vary from 0.85 to 2.4. Except in one case (FFMPEG), all the observed speedups and slowdons come from I-cache effects !
- Do not trust speedups when you work on code optimisation ! Trust what you can prove or demonstrate, not what you observ. Code quality is a matter of many metrics, speedup is a single metric among many others.