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Efficient clustering of case statements for indirect branch prediction

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Branch Prediction

- In super-pipelined processors, there is a significant lag between the beginning of the execution of an instruction and when its result becomes available.

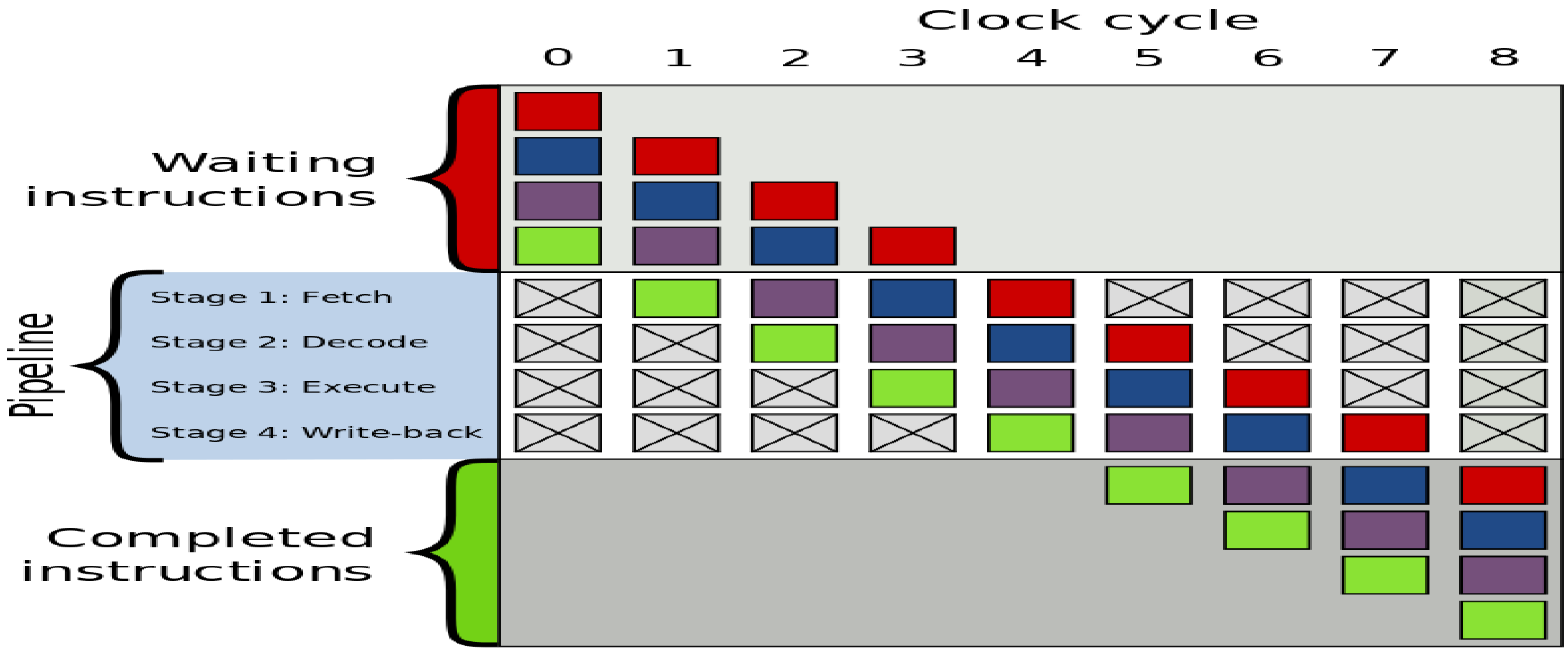


Image: "Generic 4 stage pipeline". Wikimedia Commons

Branch Prediction

- This trait also applies to conditional direct branches
  - However, waiting for the result of the instructions affecting a conditional branch is wasteful.
  - Therefore, the processor makes an educated guess as to where the conditional branch will lead to.
  - If the guess is wrong, it all goes to waste.
- Conditional direct branch prediction techniques aim at increasing the frequency when the processor makes the right guesses.

Indirect Branch Prediction

- Like conditional direct branches, indirect branches may lead to more than one target.
- Unlike conditional direct branches, which may lead to just two targets, indirect branches may lead to multiple targets.
- Therefore, indirect branch prediction techniques have traditionally been less efficient than for conditional direct branch.
- Moreover, because of multiple possible targets, predicting indirect branches needs more resources than predicting conditional direct branches, leading to more implementation compromises and limitations, depending on the transistor budget.

Jump Tables

- In the presence of a large number of conditional cases, it is more efficient to use a table of targets together with indirect branches.
  - Advantages: simple execution, compact code size.
  - Disadvantages: reliance on efficient indirect branch prediction.
- Moreover, with the increased popularity of interpreted languages and object oriented languages, many programs rely heavily on jump tables.

Jump Tables in LLVM

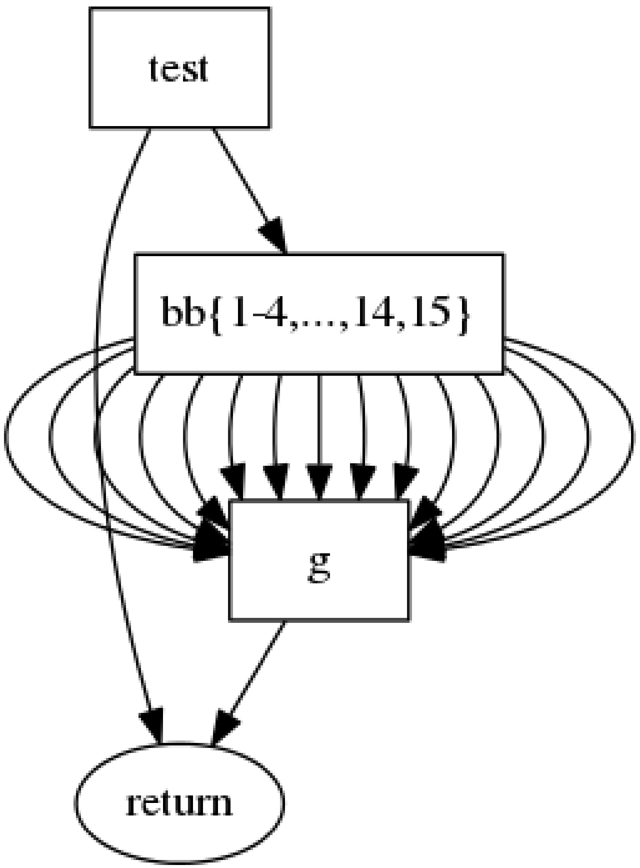
- The previous algorithm used to generate jump tables in LLVM, `SelectionDAGBuilder::findJumpTables()`, by Hans Wennborg, was based on the work by Kannan & Proebsting.
  - Minimizes the number of partitions of clusters of cases by maximizing their sizes.
  - $O(n^2)$
- However, the resulting jump tables have virtually unlimited size, which may overwhelm the processor resources dedicated to indirect branch prediction.

Jump Tables in LLVM

- The algorithm in `SelectionDAGBuilder::findJumpTables()` was modified to optionally limit the size of partitions of clusters.
  - Suiting them to the limitations of the indirect branch predictor in the target.
  - The default, unlimited size, yields the same results as before.
- Moreover, since conditional direct prediction tends to be more accurate than indirect branch prediction, it favors conditional direct branches over sparse clusters with few cases.
  - Maximizes the number of partitions of clusters by limiting their sizes.
  - Maximizes the density of clusters of cases.
    - Fewer sparse partitions, falling back to conditional direct branches.
  - O(n log n)

Jump Tables in LLVM

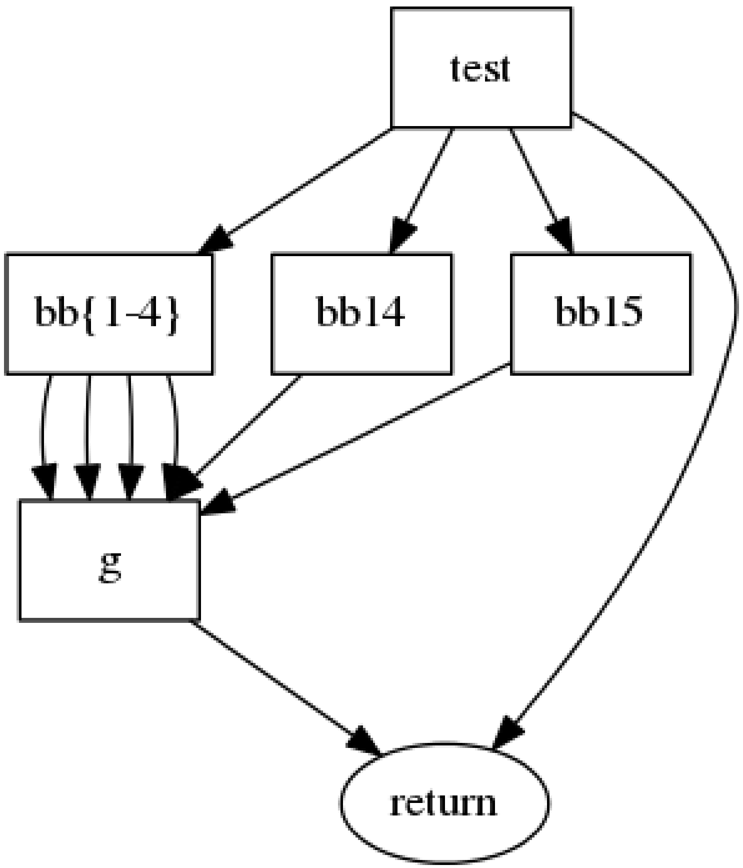
```
declare void @g(i32)

define void @test(i32 %x) {
entry:
  switch i32 %x, label %return [
    i32 1, label %bb1
    i32 2, label %bb2
    i32 3, label %bb3
    i32 4, label %bb4

    i32 14, label %bb14
    i32 15, label %bb15
  ]
return: ret void
bb1: tail call void @g(i32 1) br label %return
bb2: tail call void @g(i32 2) br label %return
bb3: tail call void @g(i32 3) br label %return
bb4: tail call void @g(i32 4) br label %return
bb14: tail call void @g(i32 5) br label %return
bb15: tail call void @g(i32 6) br label %return
}
```



-max-jump-table-size=0

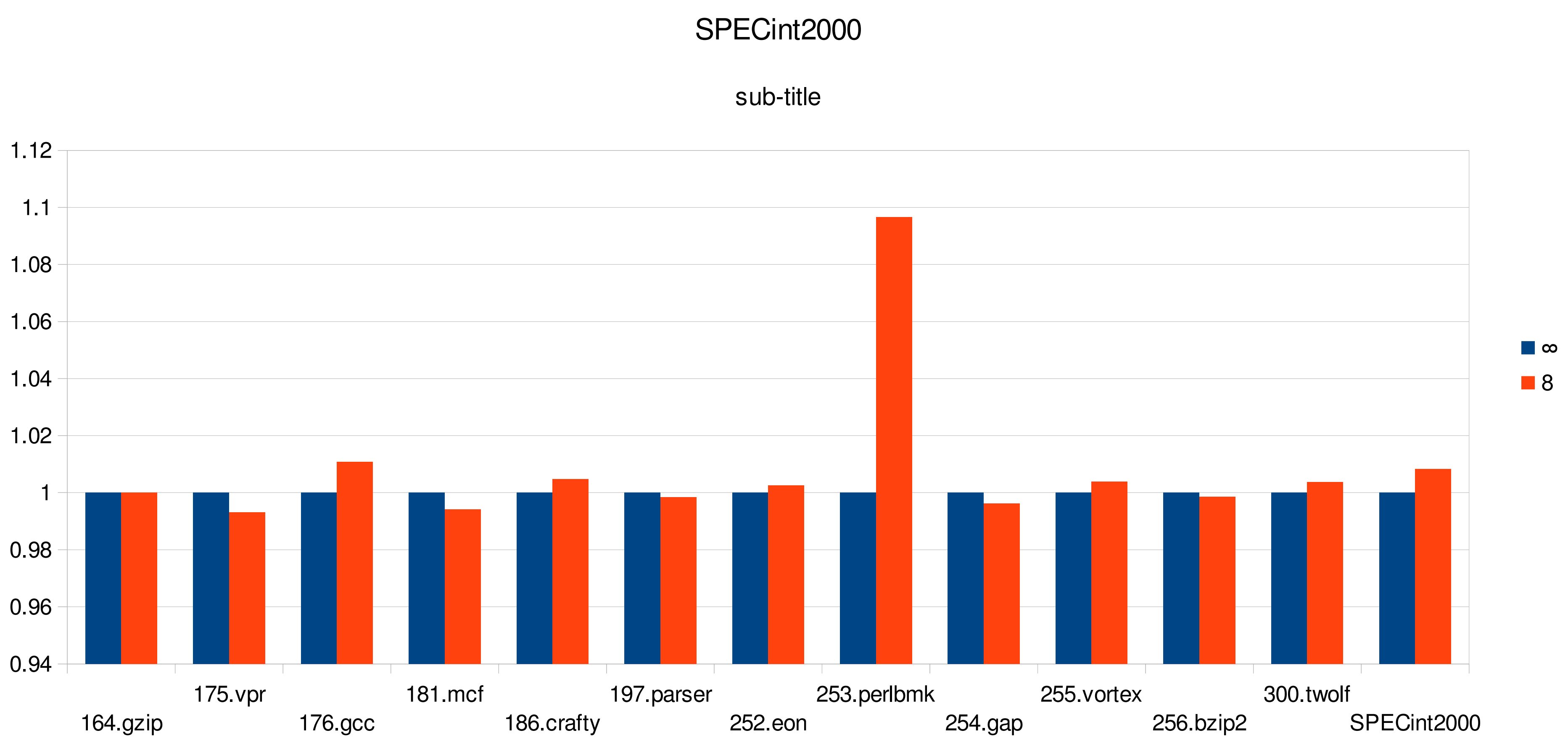
Jump Tables in LLVM

```
declare void @g(i32)

define void @test(i32 %x) {
entry:
  switch i32 %x, label %return [
    i32 1, label %bb1
    i32 2, label %bb2
    i32 3, label %bb3
    i32 4, label %bb4

    i32 14, label %bb14
    i32 15, label %bb15
  ]
return: ret void
bb1: tail call void @g(i32 1) br label %return
bb2: tail call void @g(i32 2) br label %return
bb3: tail call void @g(i32 3) br label %return
bb4: tail call void @g(i32 4) br label %return
bb14: tail call void @g(i32 5) br label %return
bb15: tail call void @g(i32 6) br label %return
}
```

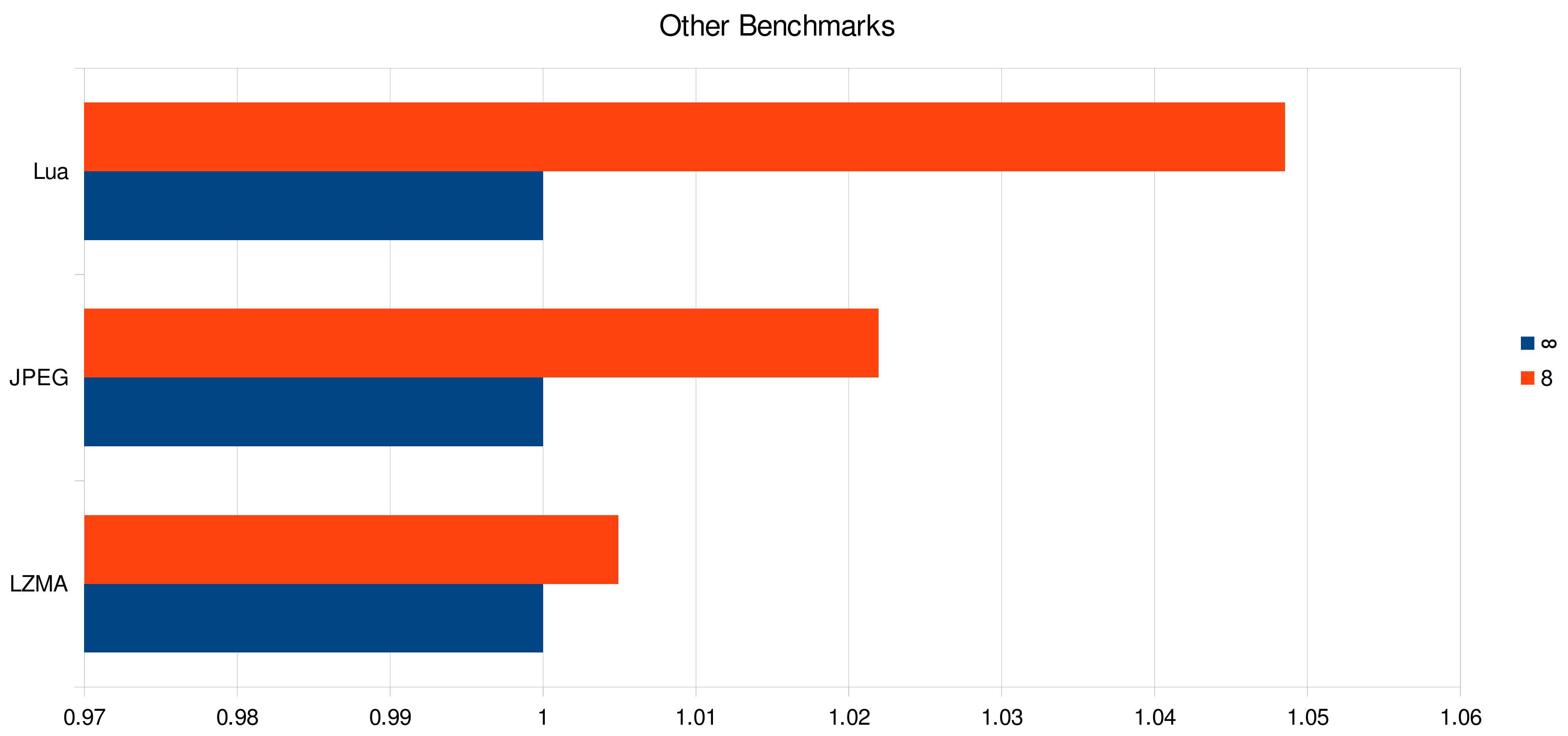


-max-jump-table-size=8

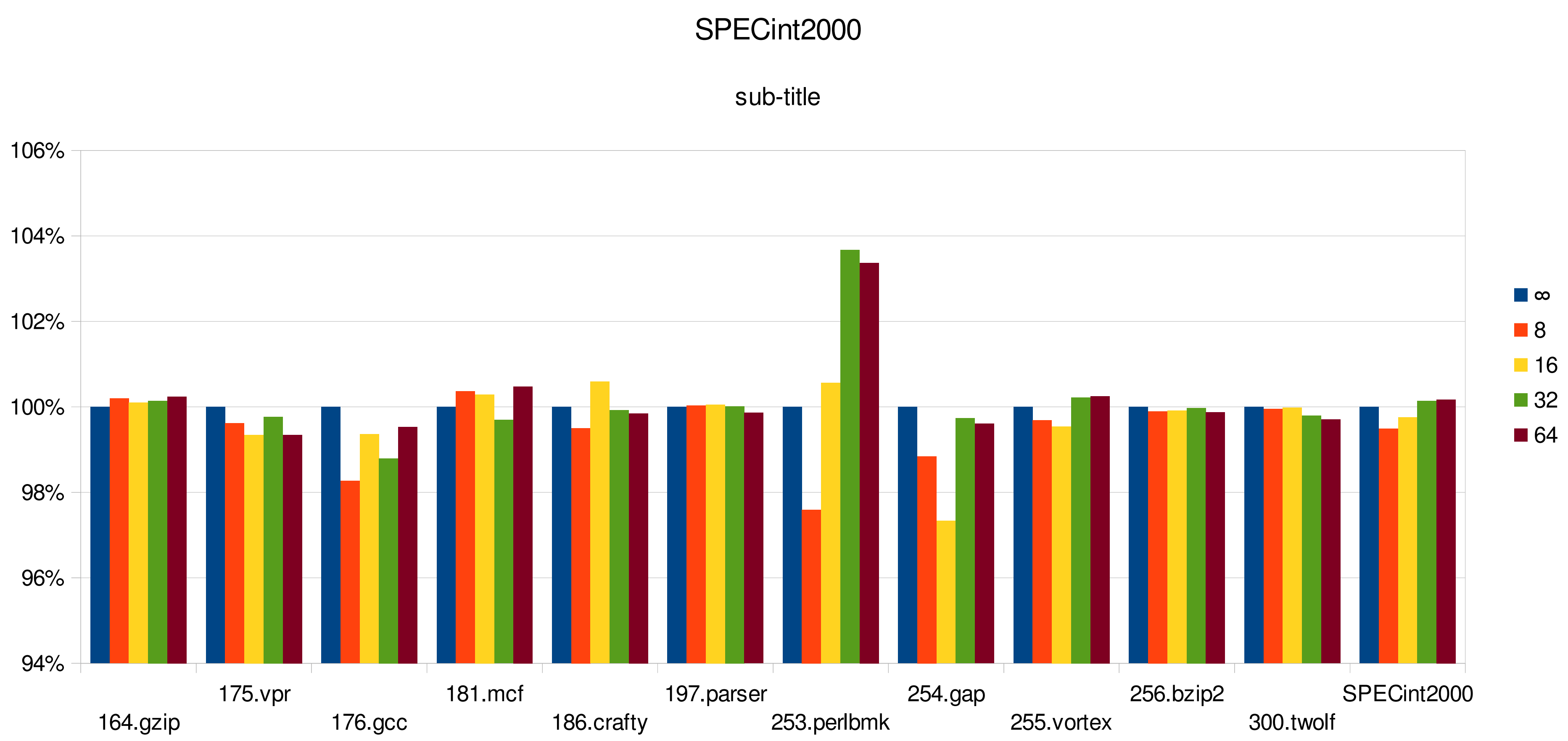
Results: Samsung Exynos M1



Results: Samsung Exynos M1

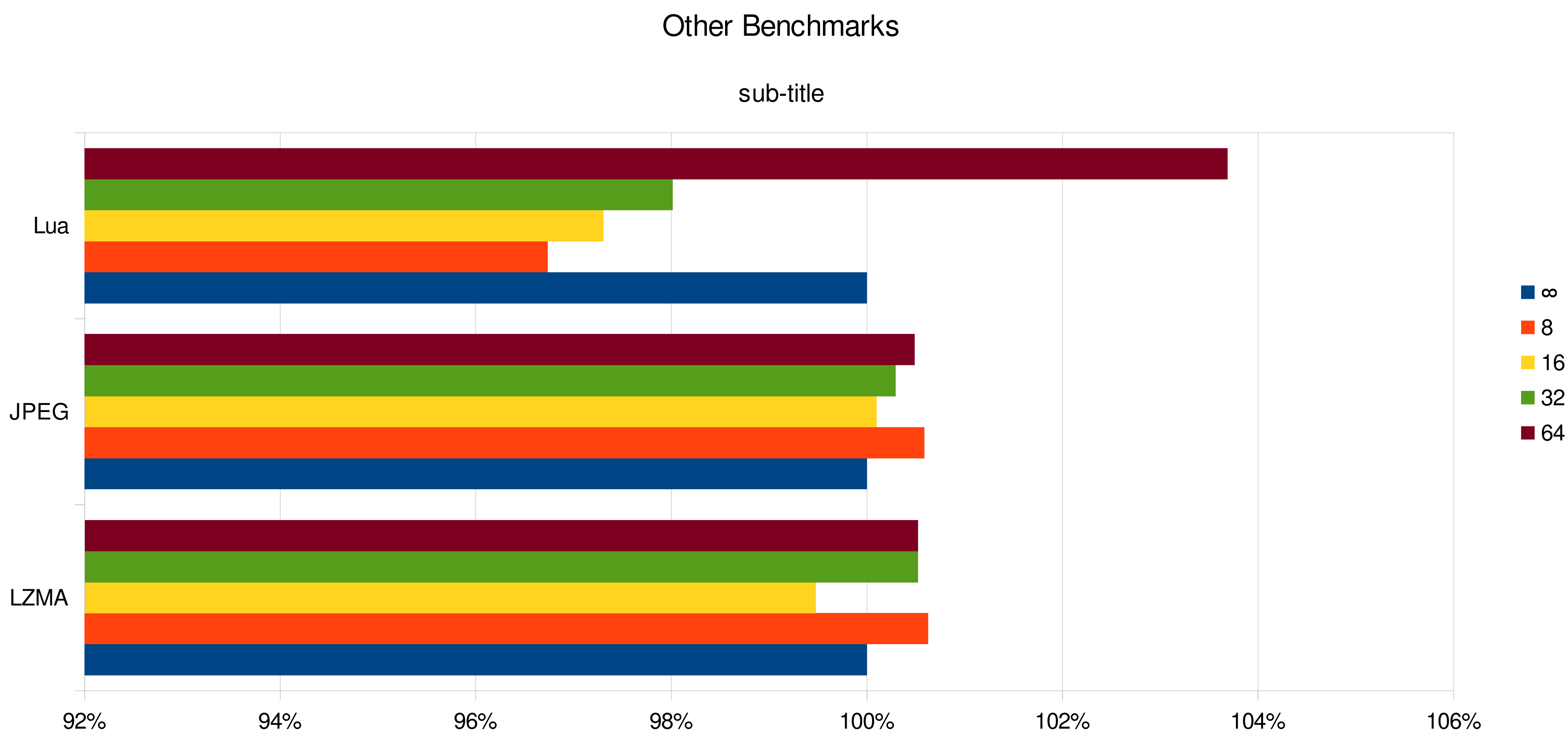


Results: ARM Cortex A57

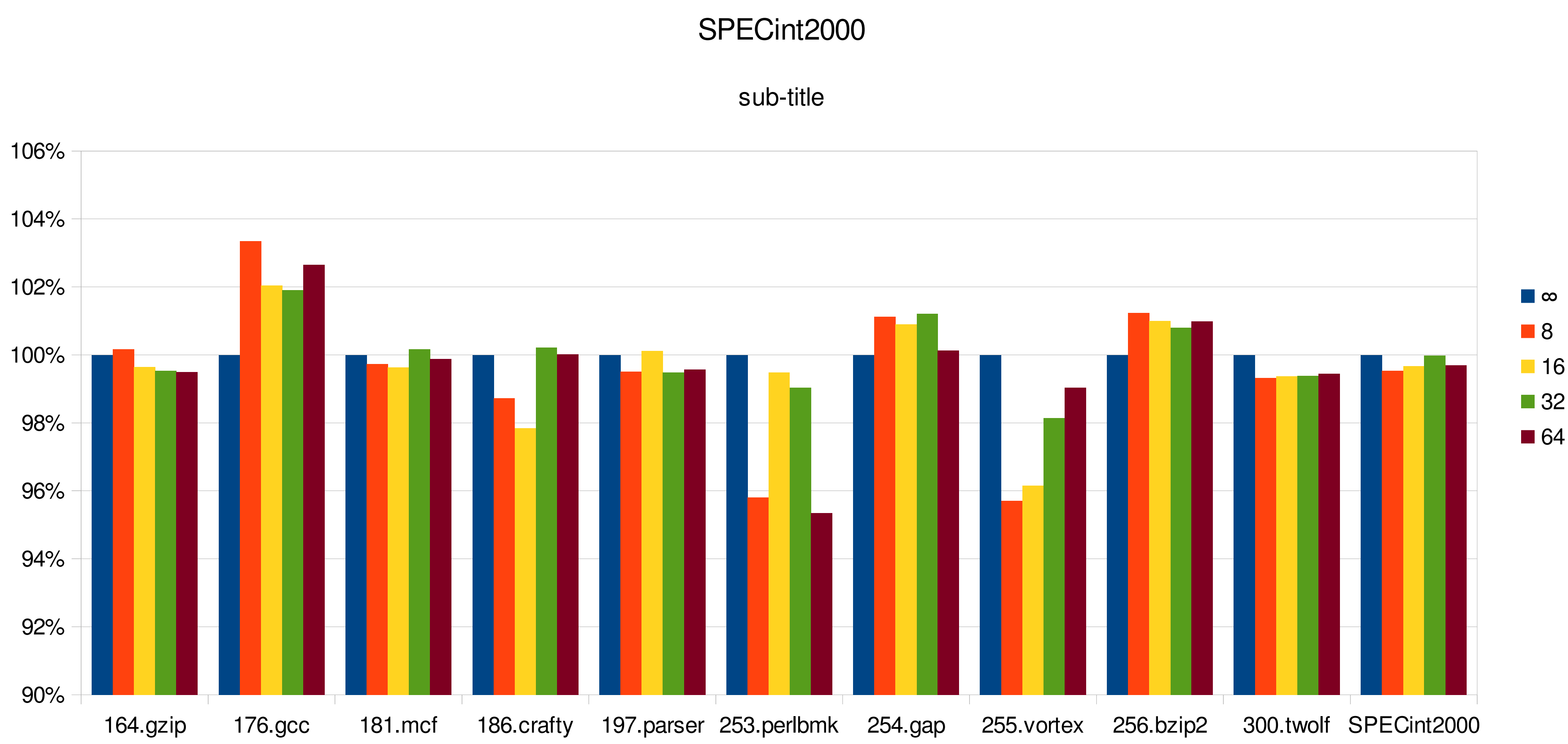


Minus 252.eon

Results: ARM Cortex A57



Results: Intel i7 Skylake



Minus 175.vpr and 252.eon

Conclusion

- The results depend largely on the implementation of the indirect branch predictor in the processor and, of course, on the workload.
  - In particular, though a jump table may have a large number of entries, only a few of them may be used in a given workload, possibly within the limitations of a particular indirect branch predictor.

Give it a try!

```
-mllvm -min-jump-table-entries=<entries>
-mllvm -max-jump-table-size=<entries>
```

References

- `llvm::SelectionDAGBuilder`
- `https://reviews.llvm.org/D21940`
- `https://reviews.llvm.org/D25212`
- Kannan; Proebsting. *“Correction to ‘producing good code for the case statement’”*, 1994.
- Lee. *“ECE 570 High Performance Computer Architecture: Dynamic Branch Prediction”,* Oregon State.
- Kim; João; Mutlu; Lee; Patt; Cohn. *“VPC Prediction: Reducing the Cost of Indirect Branches via Hardware-Based Dynamic Devirtualization”*, 2007.