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Speculative Execution and Instruction-Level Parallelism

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Abstract

Full exploitation of instruction-level parallelism by superscalar and similar architectures requires *speculative execution*, **in which we are willing to issue a potential future instruction early even though an intervening branch may send us in another direction entirely. Speculative execution can be based either on branch prediction, where we explore the most likely path away from the branch, or on branch fan-out, in which we explore both paths and sacrifice some hardware parallelism for the sake of not being entirely wrong. Recent techniques for branch prediction have greatly improved its potential success rate; we measure the effect this improvement has on parallelism. We also measure the effect of fan-out, alone and also in combination with a predictor. Finally, we consider the effect of** *fallible* **instructions, those that might lead to spurious program failure if we execute them speculatively; simply refusing to do so can drastically reduce the parallelism.**

1 Introduction

Recent years have seen a great deal of interest in *multiple-issue machines* [1, 6, 9], machines that can issue several mutually independent instructions in the same cycle. These machines exploit the parallelism that programs exhibit at the instruction level.

It is important to know how much parallelism is available in typical applications. Machines providing a high degree of multiple-issue would be of little use if applications did not display that much parallelism. The available parallelism depends strongly on how hard we are willing to work to find it. Recent studies studies [4, 5, 6, 13, 14, 15, 16, 17] have led to a growing consensus that high levels of parallelism are available only by doing *speculative execution*, in which we can issue an instruction whose data dependencies are satisfied even though its control dependencies are not. That is, we issue a potential future instruction early even though an intervening branch may send us in another direction entirely.

There are two approaches to the selection of instructions to execute speculatively. We can do *branch prediction,* trying to guess whether a conditional branch will be taken so we know which of the two possible paths to follow in selecting instructions. Or we can *fan out* and select instructions from both possible paths, spending some of our machine parallelism for the assurance that at least some of the instructions we speculatively execute will be useful. It is possible to use a combination of the two, fanning out part of the time and predicting the rest of the time.

This paper presents results concerning three questions. First, recent work in branch prediction [8, 10, 18, 19] has shown how to use very large predictors to improve the performance of hardware predictors from around 92% success to around 98%. What effect does this have on instruction-level parallelism? Second, how useful is a fan-out capability, both by itself and in combination with a predictor? Third, on some architectures certain instructions must not be executed speculatively because they can cause run-time exceptions. Does this cripple a multiple-issue machine, or can it be tolerated?

We start with an overview of branch prediction and fan-out techniques. We then describe our experimental environment, based like many others on trace-based simulation. Finally we present our results, and some conclusions.

2 Branch prediction

Branch prediction can be done statically or dynamically. Static prediction based on the direction of the branch or other heuristics is only somewhat effective, but prediction based on a profile of a previous run of the application is successful around 90% of the time. Dynamic prediction is normally done in hardware, with the prediction for a given branch based on recent events in the execution. A common hardware branch predictor [7, 12] maintains a table of saturating two-bit counters. Low-order bits of a branch's address provide an index into this table, associating a counter with each branch; if the table is small then the program space wraps around, possibly associating the same counter to several branches across the program. We predict that a branch will be taken if the associated counter is 2 or 3, and otherwise predict not taken. Later, when the branch is resolved, we increment the counter if it *was* taken, and otherwise decrement it. A predictor of 512 counters is successful about as often as a profile, but unfortunately increasing the size of the table does not help much; the success rate levels off at 92% or 93% regardless of the table size.

Recent studies have explored more sophisticated hardware prediction using *branch histories* [10, 18, 19]. These approaches maintain tables relating the recent history of the branch (or of branches in the program as a whole) to the likely next outcome of the branch. These approaches do quite poorly with small tables, but unlike the two-bit counter schemes they can benefit from much larger predictors.

An example is the *local-history* predictor [18]. It maintains a table of n-bit shift registers, indexed by the branch address as above. When the branch is taken, a 1 is shifted into the table entry for that branch; otherwise a 0 is shifted in. To predict a branch, we take its n-bit history and use it as an index into a table of 2^n 2-bit counters like those in the simple counter scheme described above. If the counter is 2 or 3, we predict taken; otherwise we predict not taken. If the prediction proves correct, we increment the counter; otherwise we decrement it. The local-history predictor works well on branches that display a regular pattern with a small period.

Sometimes the behavior of one branch is correlated with the behavior of another. A *global-history* predictor [18] tries to exploit this effect. It replaces the table of shift registers with a single shift register that records the outcome of the n most recently executed branches, and uses this history pattern as before, to index a table of counters. This allows it to exploit correlations in the behaviors of nearby branches, and allows the history to be longer for a given total predictor size.

An interesting variation is the *gshare* predictor [8], which uses the identity of the branch as well as the recent global history. Instead of indexing the array of counters with just the global history register, the gshare predictor computes the `xor` of the global history and branch address.

McFarling [8] got even better results by using a table of two-bit counters to dynamically choose between two different schemes running in competition. Each predictor makes its prediction as usual, and the branch address is used to select another 2-bit counter from a *selector* table; if the selector value is 2 or 3, the first prediction is used; otherwise the second is used. When the branch outcome is known, the selector is incremented or decremented if exactly one predictor was correct. This approach lets the two predictors compete for authority over a given branch, and awards the authority to the predictor that has recently been correct more often. McFarling found that combined predictors did not work as well as simpler schemes when the total predictor size was small, but did quite well indeed when large.

3 Branch fan-out

Rather than try to predict the destinations of branches, we might speculatively execute instructions along *both* possible paths, squashing the wrong path when we know which it is. Some of our hardware parallelism capability is guaranteed to be wasted, but we will never miss out completely by blindly taking the wrong path. Unfortunately, branches happen quite often in normal code, so for large degrees of parallelism we may encounter another branch before we have resolved the previous one. Thus we cannot continue to fan out indefinitely: we will eventually use up all the machine parallelism just exploring many parallel paths, of which only one is the right one.

In some respects fan-out duplicates the benefits of branch prediction, but they can also work together. We explore both paths up to the fan-out limit, and then explore only the predicted path beyond that point.

4 Fallible instructions

In most architectures, some instructions can fail, causing an exception. Examples are memory references, which can cause segmentation violations, and floating-point operations, which can cause several kinds of traps. Speculatively executing a fallible instruction is dangerous, because it might make a correct program fail; to avoid this, the hardware must somehow make the exception itself speculative, so that the failure does not occur until we are sure that the instruction should have been executed.

The easy way out is simply to refuse to speculatively execute a fallible instruction. This is likely to degrade the parallelism, since it will also delay safe instructions that depend on the fallible instruction, but it eliminates the need for hardware trickiness.

5 Simulation environment

To study the effects of these issues on instruction-level parallelism, we used the trace-based simulator described in detail in an earlier report [17]. An instruction trace of the application is passed, one instruction at a time, to the scheduler. The scheduler places each instruction into some cycle of a sequence of pending cycles, subject to dependencies with previously scheduled instructions. Whether there is a dependency is determined by the parallelism model we use. If the model does not include branch prediction, for example, then each instruction appearing after

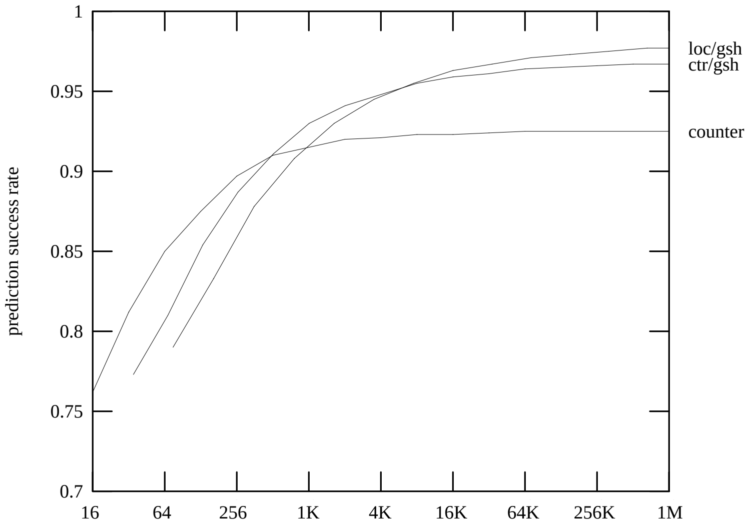

Figure 1: Fraction of branches predicted correctly by three different prediction schemes, as a function of the total number of bits in the predictor

a branch in the trace must be scheduled after that branch in the pending cycles. If the model does include branch prediction, in contrast, we can schedule later instructions into cycles before the branch, if the predictor is successful; otherwise we must assume that a real machine would have speculatively executed instructions from the wrong path, and would only start looking down the correct path when execution of the branch instruction reveals the misprediction.[1]

The simulator uses a greedy scheduling algorithm, placing each instruction as early as possible in the pending cycles, given the instructions that preceded it in the trace. Each cycle can hold a maximum of 64 instructions, and the entire sequence of pending cycles can hold 2048 instructions. When the number of pending instructions exceeds that number, we "issue" the first cycle, which prevents us from scheduling any more instructions in it.

For the purposes of this paper, the parallelism model simulated is specified by four parameters: branch prediction and fan-out, fallibility, register renaming, and memory disambiguation. The full system is somewhat more flexible than this.

In this paper we are interested in the effect of varying the size of the branch predictor. Different predictors do the best in different regions of this spectrum of size. Figure 1 shows the harmonic

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[1] This approach to a missed prediction ignores the possibility that code could be moved from after the point where the paths rejoin to a position before the paths split apart. Recognizing such opportunities is difficult in hardware but feasible in a software scheduler [4, 14].

mean of the success rates of three predictors for twelve SPEC92 benchmarks, as the predictor size varies. The two-bit-counter predictor does best for predictor sizes up to 512 bits. A predictor built by combining a counter predictor and a gshare predictor does best in the middle range up through 4K bits, and a combination of a local predictor and a gshare predictor works best above 4K bits. Throughout this paper, when we speak of a predictor of a particular size, the range that includes this size will determine the prediction technique used.

Branch fan-out is a little trickier to model. We want to explore both paths away from a branch, but the simulator has only the correct instruction trace to work from and therefore cannot actually schedule instructions from paths not taken. Exploring these false paths on a real machine would use up hardware parallelism, however, especially since we will likely have to schedule another branch before the first is issued and resolved. We model this approximately by assuming that there is a *fan-out limit* on the number of branches we can look past. If our model has a non-zero fan-out limit, we can handle branches beyond that limit either by giving up or by conventional branch prediction.

There are two kinds of instructions we can consider fallible: floating-point binary operations and memory-reference instructions. In this paper we arbitrarily allowed only heap references to fail, on the perhaps generous assumption that program analysis or language semantics could preclude the failure of references to stack or static data.

This paper is not directly concerned with the effects of register or memory dependencies. To provide a small selection of contexts for our exploration of branch analysis and fallibility, however, we assumed four different base models. The *alpha* model assumes perfect memory disambiguation, so that a store conflicts with a load or store only if the two actually reference the same word in memory, and assumes an infinite number of registers with a perfect renaming scheme, so that we never have output dependencies or antidependencies between registers. The *beta* model also assumes perfect memory disambiguation, but assumes 64 CPU registers and 64 FPU registers, managed dynamically by a hardware renaming scheme using an LRU discipline (relative, of course, to the position in the scheduled cycles rather than in the instruction trace). The *gamma* model assumes perfect memory disambiguation and *no* register renaming, so that register conflicts are determined by the registers actually allocated by the DECstation compiler. The *delta* model assumes no register renaming and simple but very conservative memory disambiguation by *instruction inspection*, a common technique used in compile-time instruction-level pipeline schedulers: two instructions do not conflict if (a) they use they use the same base register but

	register renaming	*memory disambiguation*
alpha	infinite	perfect
beta	64 int, 64 fp	perfect
gamma	no renaming	perfect
delta	no renaming	inspection

Figure 2: The four base models of register renaming and memory disambiguation

different displacements, or (b) one uses a register known to point to the stack and the other one known to point to the global data area. Figure 2 summarizes these four models.

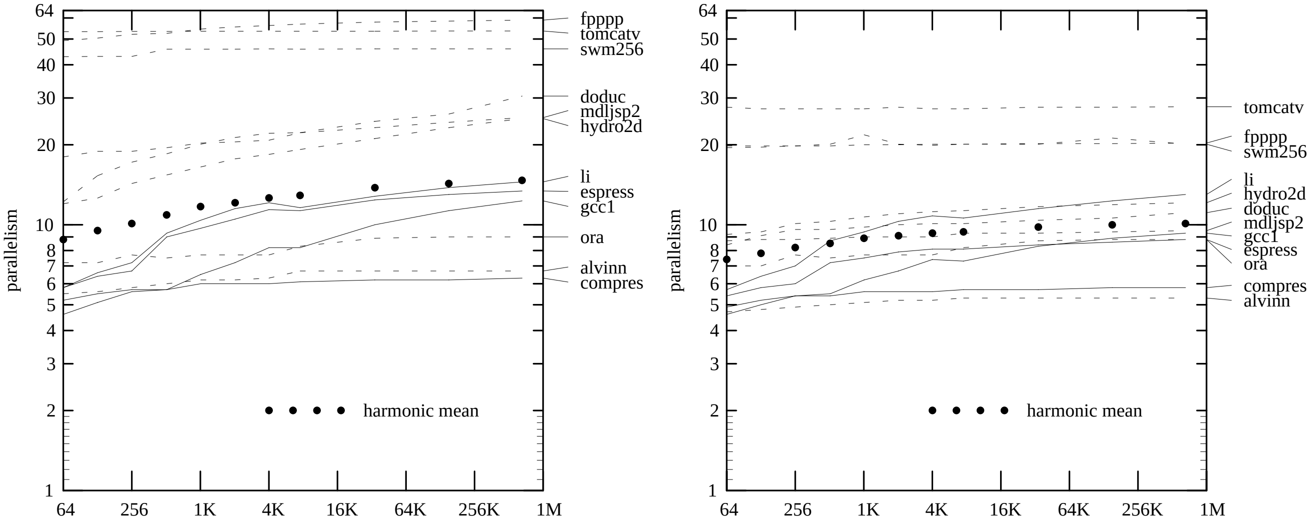
In all four of these models we assume that all indirect jumps (chiefly procedure returns, calls to procedure variables, and case-statement indexed jumps) are predicted perfectly. Procedure returns are easy to predict with simple hardware, but other jumps are less so. Assuming perfect jump prediction is therefore generous but probably not consequential; indirect jumps are rare enough in the programs we tested that jump prediction has a significant effect on parallelism only when branch prediction is also perfect.

All of our simulations were done with a set of twelve programs from the SPEC92 suite. (The rest of them run too long for our simulation to be feasible.) We usually gave them the official "small" data sets where possible, and in the case of tomcatv and alvinn we modified the value of a constant to reduce the number of iterations of the outer loop.

6 Results

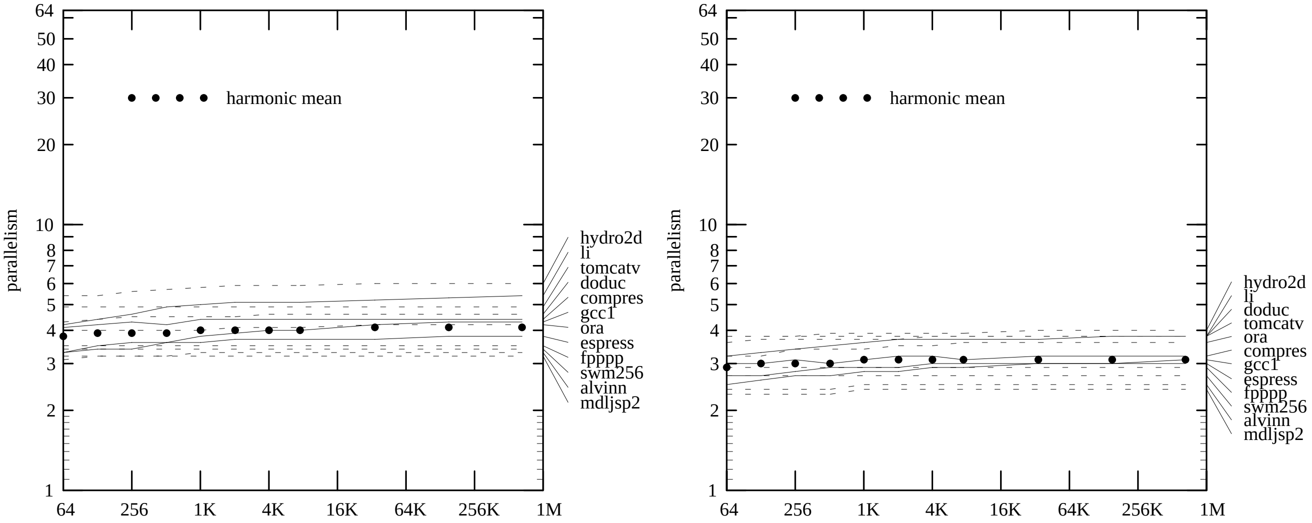
Our first experiment measured the parallelism as the total size of the branch predictor increased. As described earlier, different predictors have better success rates in different size ranges, so we use different predictors for the small, intermediate, and large predictor sizes. (This is why some benchmarks show a sudden change around 512 bits or 4K bits.) Figure 3 shows the results for each of our four base models. The solid curves are integer benchmarks; the dotted curves are floating-point benchmarks.

Under the *alpha* model, with infinite registers and perfect memory disambiguation, we see



(a) infinite registers and perfect memory disambiguation

(b) 64 renamed registers and perfect memory disambiguation



(c) no register renaming and perfect memory disambiguation

(d) no register renaming and memory disambiguation by inspection

Figure 3: Effect of branch predictor size on parallelism

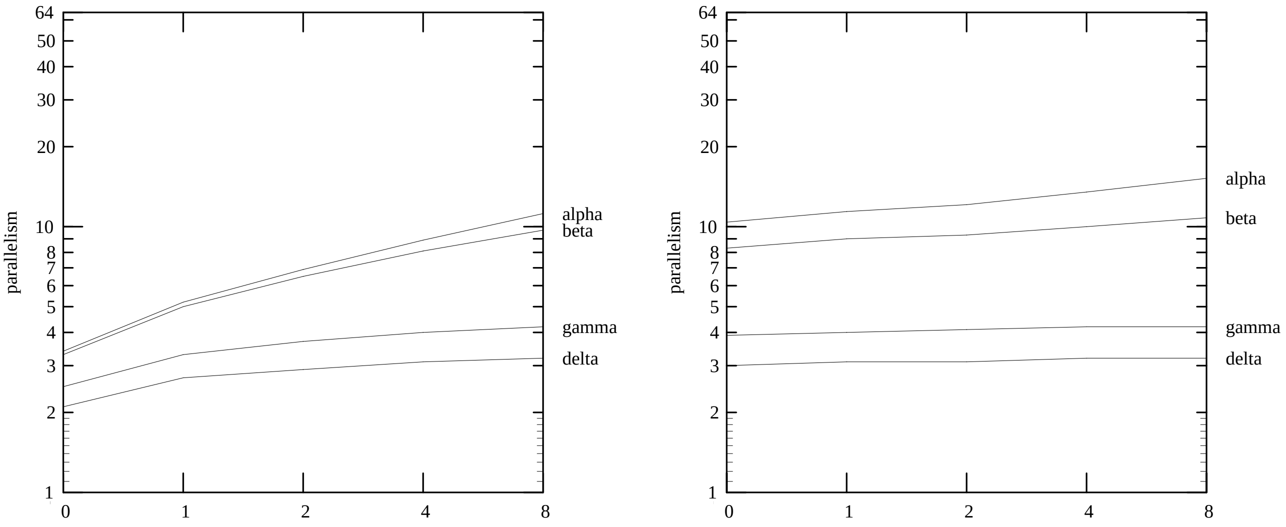


Figure 4: Effect of fan-out on parallelism without branch prediction (left) and with a 0.5-kilobit branch predictor (right)

that a few programs benefit considerably from large predictors. Gcc1 continues to improve even as we reach a predictor of three-quarters of a megabit. Both li and espresso improve 40% between 1 kilobit and 1 megabit; the harmonic mean of the improvements over that range is 25%. It is interesting that the programs least sensitive to the size of the predictor are those most parallel and those least parallel.

Under the *beta* model we see roughly the same behavior, though it is not as pronounced. Now the mean payoff of the biggest predictor over the 1-kilobit predictor is about 14%. When we eliminate first register renaming and then perfect memory disambiguation, we see that the advantage of a very large predictor evaporates almost completely. The largest improvement from 1Kb is 13%, but few programs do even close to this well; the mean is more like 2%.

Unsurprisingly, we see that a very large branch predictor can be helpful, but only if we get everything else right.

Next we consider the effects of fanning out at branches. Figure 4 shows the mean parallelism over the 12 programs as the fan-out limit increases, for each of the four base models. The left-hand graph assumes that the fan-out capability is working alone, without subsequent branch prediction: when the fan-out limit is reached we can look beyond no more branches for instructions to issue.

The right-hand graph assumes that fan-out is followed by branch prediction: when the fan-out limit we can continue to look past branches for instructions, but only along the predicted path. The predictor used is a modest one, a simple counter-based predictor of 256 entries. [2]

Without branch prediction, a little fan-out helps a lot, even in the poorer base models. Fanning out past just 1 level of branching improves the parallelism of *gamma* and *delta* by around 30%, and of *alpha* and *beta* by around 50%. Increasing the fan-out limit continues to improve things significantly, but the effects are not as dramatic.

Interestingly, fanning out even to a level of 8 branches gives us a parallelism in each model that is nearly the same as the parallelism from using the half-kilobit predictor with no fan-out at all. Adding eight levels of fan-out to this predictor improves the parallelism somewhat, by 30-45% in *alpha* and *beta*, and by about 7% in *gamma* and *delta*.

Thus an ambitious fan-out capability could be an adequate substitute for branch prediction, though it is hard to imagine the circumstances in which it would be easier to implement. Adding branch prediction to even a modest predictor does not buy us much unless (again) we do a very good job of handling register and memory dependencies.

We assumed that two kinds of instructions could fail: binary floating-point operations, and heap memory references. In the actual traces, of course, these operations never fail; since we could not know that in advance, we model their fallibility by insisting that they always be scheduled later than any previous branch. We also experimented with models in which only one of these two classes of instructions are fallible. These proved uninteresting, because the behavior of the twelve SPEC92 programs is bimodal: the integer programs do essentially no floating-point operations, and the floating-point programs make few or no heap references. In either case, assuming that only one could fail gave results essentially identical to assuming that neither or both could fail.

Figure 5 shows the results, for the four base models and two different predictor sizes. We have separated out the integer from the floating-point programs, and present the harmonic mean parallelism for each. The upper curve in each pair is the parallelism without fallible instructions; the lower is with fallible instructions.

Fallibility has a larger effect on the integer programs than on the floating-point programs. It

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[2] The simulator's viewpoint is the reverse of the hypothetical hardware's. The simulator schedules each successive instruction into one of the pending cycles, so to implement a fan-out of n without prediction it allows the instruction to be scheduled earlier than the previous n branches, but not the $n + 1$st. To implement fan-out followed by branch prediction, we tentatively predict every branch, and allow an instruction to be scheduled before any number of successfully predicted branches, preceded by n more branches whether predicted successfully or not. In other words, the instruction must be scheduled after the nth branch before the last incorrectly predicted branch.

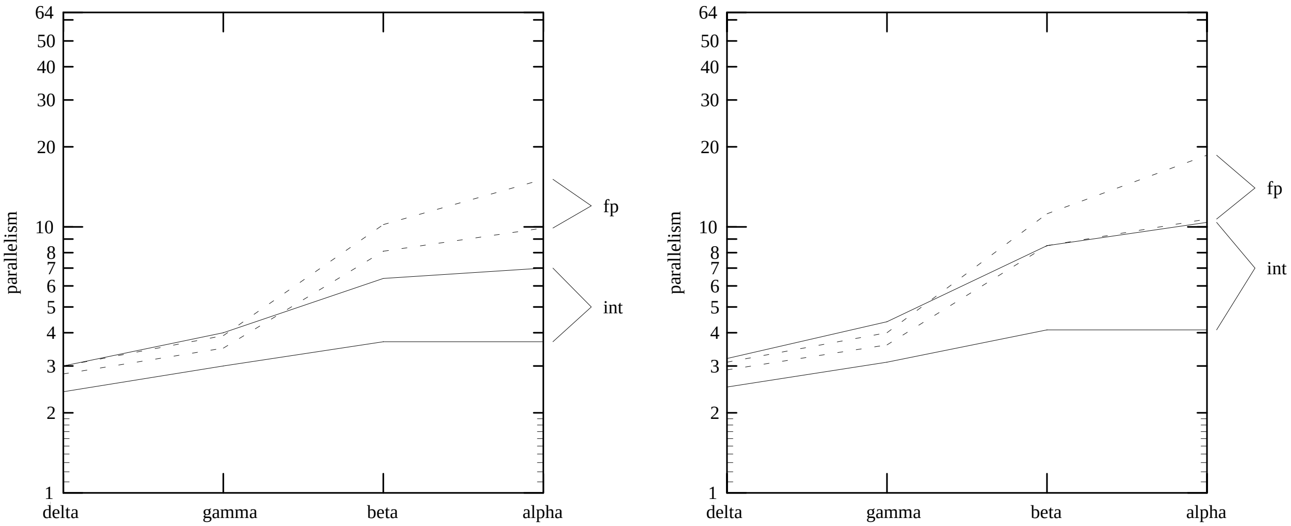

Figure 5: Effect of fallible instructions on parallelism with 0.5-kilobit branch predictor (left) and with 0.7-megabit branch predictor (right)

reduces the parallelism of integer programs so much that the most ambitious model has barely half again the parallelism of the poorest.

Fallibility has its greatest effect on the more ambitious models. It can cut the parallelism of a good model in half but rarely reduces the smaller parallelism of a poorer model by more than a fifth. Evidently (and perhaps obviously) the more different kinds of bottlenecks to scheduling you have, the less another one matters.

7 Conclusions

The qualitative conclusions of this study should come as no great surprise, though we hope the quantitative results will serve as useful hints to the architecture and compiler communities.

Very good branch prediction from megabit history-based predictors can significantly improve parallelism, though the magnitude of this improvement was not as great as we had hoped to see. The payoff of a large predictor is probably negligible unless we also take strong action to reduce false register dependencies and disambiguate memory references.

Fanning out across many levels of branches can in principle be a substitute for modest branch prediction, though a large predictor has no trouble beating it. Since fan-out is likely to be harder to implement than ordinary prediction, it is probably more interesting to note that adding fan-out to prediction can improve it. As before, however, the improvement is significant only if we have false register and memory conflicts well under control.

These results confirm that we really need to work with a combination of very good techniques if we want to achieve high levels of parallelism. It is therefore important to note that refusing to execute fallible instructions speculatively can halve the parallelism of the more ambitious models. Techniques that allow failures to be postponed until we are sure they were supposed to happen [2, 3, 11] are essential to the full exploitation of instruction-level parallelism.

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