

Utilizing Parallel Workers: LLVM’s Vectorization Plan

Jonas Fritsch

Technical University of Munich

jonas.fritsch@tum.de

Abstract

Lorem ipsum

1 Introduction

Modern CPUs are often equipped with multiple different vector registers. These registers are nowadays as wide as 512 bits, allowing for the processing of multiple data streams at once (SIMD). By batching multiple values together in one register, different ISAs like Intel AVX or ARM SVE allow the execution of the same instruction for all values in a vector register simultaneously. Utilizing this leads to significant performance improvements over the scalar equivalent most of the time.

However, manual code vectorization can quickly become time-consuming, especially when supporting different CPU architectures. Modern compilers aim to automatically transform scalar code to use vectorization when applicable.

As one of the most widely used compilation frameworks, LLVM [3] has implemented and refined its auto-vectorization over many years. It provides two different Vectorizers, one for innermost loops (LoopVectorizer) and one for super-word parallelism (SLPVectorizer) [10].

This system, however, had quite a few limitations, as the loop vectorizer could only handle innermost loops and neither outer loops, complex control flow, nor non-inlined functions. Additionally, while multiple different vectorizations for the same scalar code would be possible, the current vectorizers working directly on the LLVM IR could not model and compare the costs of such different vectorization approaches.

With these limitations in mind, Intel started an ongoing refactorization effort to migrate LLVM’s auto-vectorization pipeline to utilize a more abstract Vectorization Plan (VPlan) [8, 11]. The final goal would be to unite LLVM’s auto-vectorization in a single flexible system capable of optimizing

SLPs, inner, and nested loops with complex control flows. The auto-vectorization pass would create and transform multiple different VPlans, each modeling a different vectorization approach, abstracted away from the underlying LLVM IR. Those VPlans are compared against each other based on a cost model, and finally, the best one, which might also not vectorize at all, is materialized into the LLVM IR.

LLVM’s VPlan is currently being integrated into the existing Loop Vectorizer and is already modeling most inner loop vectorizations and transformations [2]. Vectorization for outer loops is also in development and can be enabled by setting the `-enable-vplan-native-path` flag [1]. In the future, the plan will be to merge both of these loop vectorization paths into one. Merging the existing SLP Vectorizer with VPlan is also planned.

2 Background

In general, vectorization techniques can be separated into different categories:

2.1 Inner Loop Vectorization

Innermost loops are loops whose body’s control flow does not contain any more loops, bound or unbound. Vectorization of these loops is more straightforward as the only option to vectorize is over the loop’s induction variable.

There are various ways to transform the control flow of a loop to accommodate operating on widened vector registers. Figure 1 shows an example of an if-conversion. Some more examples can also be found in LLVM’s Auto-Vectorization Documentation [10].

2.2 Super-Word Parallelism (SLP) Vectorization

SLP Vectorization vectorizes similar independent instructions. A compiler might have, for example, fully unrolled a smaller loop in a previous code

```

1  for (int i = 0; i < N; i++) {
2      if (z[i]) {
3          x[i] += y[i];
4      }
5  }

```

Figure 1. A code snippet of a simple loop that would be vectorized over the variable *i*. The conditional branch would be flattened into a masked addition. The mask would be generated based on *z[i]*.

```

1  for (int i = 0; i < N; i++) {
2      float sum = 0;
3
4      for (int j = 0; j < 6; j++) {
5          sum += y[j][i] * z[j];
6      }
7
8      x[i] = sum;
9  }

```

Figure 2. A code snippet of a nested loop where it would be beneficial to vectorize over the outer loop. The inner loop has a trip count that is too low (6) to vectorize. Additionally, the memory access pattern of *y* would be consecutive compared to scattered when vectorizing over *i* instead of *j*.

simplification pass. The resulting similar scalar instructions might then be vectorized later by an SLP vectorizer.

2.3 Outer Loop Vectorization

Outer loop vectorization focuses on control flow with nested loops. Such loops often present more challenges for auto-vectorization, as one could vectorize over the outer loop, inner loop, or a mix of both, representing a hybrid/multi-dimensional vectorization approach. Carrying out and comparing costs of such different vectorization approaches can be complex and require a flexible system like, for example, VPlans.

Figure 2 shows a nested loop code snippet where vectorization over the outer loop would be beneficial.

2.4 Function Vectorization

Function vectorization refers to the vectorization of entire functions. A loop might contain a non-inlined function call, passing data related to the iteration variable. During auto-vectorization, this call could be replaced with a call to a newly constructed function with the same semantic control flow but operating on multiple values at once through vector registers instead.

2.5 Vectorization Similarities

All of the above-mentioned vectorization techniques can be brought into relation with each other. For example, function vectorization can be transformed into loop vectorization by creating a loop around the function body and vectorizing it and vice versa. The same applies for SLP Vectorization and loop vectorization when unrolling a loop.

2.6 Vectorization Legality

Not all loops can be vectorized. There are various factors that can ultimately hinder any vectorization attempts.

Some of the most common vectorization barriers are data dependencies. As the vectorized version of a code executes for *N* (Vectorization Factor) data streams simultaneously, it inherently changes the order of operations. To guarantee that the semantics of the code do not change, all operations on these *N* data streams must, generally, be independent. The simplest case where this is not provided is when the *i*-th loop iteration depends on any of the (*i* - *N*)-th previous iterations.

While explicit data dependencies are easier to see, even a simple loop, as in Figure 1, could carry an implicit dependency in line 3, if the *x* and *y* point to overlapping memory regions (pointer aliasing).

Not all data dependencies directly hinder any vectorization. One exception can sometimes be made for reduction idioms, as seen in the inner loop in Figure 2, where *sum* would be a reduction variable.

Additionally, the control flow should be primarily straight-line code. While most if-else constructs can be flattened to always execute both branches along with masking, the same is not valid for switch-case statements or too complex control flows.

2.7 Vectorization Costs

While it may not be legal to vectorize a given control flow, the vectorized code sometimes performs worse than its scalar equivalent.

Some control flow transformations that seem beneficial at compile time might reveal a performance bottleneck at runtime. Considering the code snippet from Figure 1, it might be that almost all `z[i]` evaluate to false at runtime. The branch predictor of a CPU would then be able to guess the correct branch in the scalar code. The vectorized version would always load the `y[i]` into memory only for the addition to be masked away. Different approaches to avoid such runtime penalties are branch-on-superword-condition code (BOSCC) [4, 9] or active-lane consolidation (ALC) [5, 6].

Some vector instructions can be costly on most CPUs. Examples are gather, scatter, shuffle, and permutation instructions. Control flow with many non-adjacent memory loads/stores or operations that combine different vector elements, such as reductions, can decrease vectorization performance.

Additionally, the vectorized code size will always be larger than the scalar equivalent. This is due to many factors: (1) The transformed control flow often includes more instructions. (2) As the loop trip count might not be a perfect multiple of the vectorization factor, a scalar epilogue/remainder of the loop might be used to handle the tail iterations. (3) Various runtime checks might be inserted throughout the vectorized control flow to handle, for example, pointers to overlapping memory regions, in which case the scalar version of the loop is executed.

3 LLVM's Vectorization Plan

Originally LLVM implements two different vectorizers for auto-vectorization, LoopVectorize (LV) and SLPVectorize. These vectorizers are a part of LLVM's middle-end and run after module simplification. As VPlan has not yet been integrated into SLP-Vectorization we will only focus on explaining the original LoopVectorize structure.

LoopVectorize was designed to focus only on vectorization of innermost loops [7]. When starting with a initial scalable loop in IR it will first run a legality phase to check whether and how it is legal to vectorize the loop. This phase would produce artifacts like if and what runtime aliasing checks

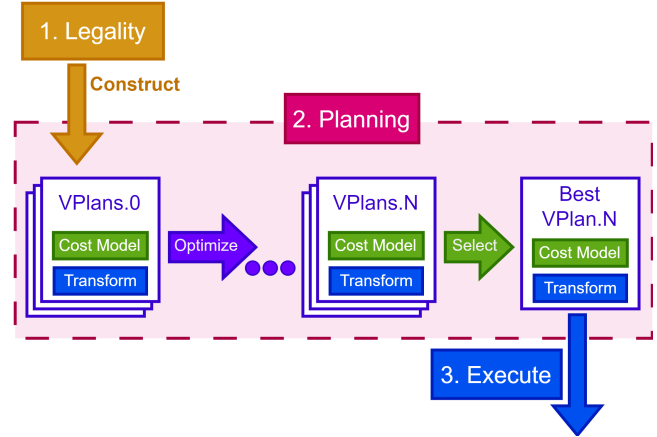


Figure 3. The planned future architecture for VPlan. The VPlan optimization would work as iteratively applying VPlan-to-VPlan transformations.

would be required. If some vectorization would be legal the cost model would run next, creating more artifacts based on the scalar IR and legality artifacts. These cost model artifacts would associate different vectorization possibilities with a fixed cost. Lastly the transformation phase would vectorize the underlying IR based on all the produced artifacts.

However, this LoopVectorize architecture had several problems. For once extending the rigid system to include outer loop and nested loop vectorizations would have been very challenging.

3.1 State of Vectorization Plan (VPlan)

3.2 Future of VPlan

4 Related Work

Lorem ipsum

5 Summary and Future Work

Lorem ipsum

References

- [1] Diego Caballero and Intel Vectorizer Team. 2018. Extending LoopVectorize to Support Outer Loop Vectorization Using VPlan. <https://llvm.org/devmtg/2018-04/slides/Caballero-Extending%20LoopVectorize%20to%20Support%20Outer%20Loop%20Vectorization%20Using%20VPlan.pdf> Accessed: 2024-11-18.
- [2] Florian Hahn and Ayal Zaks. 2023. VPlan: Status Update and Future Roadmap. <https://llvm.org/devmtg/2023-10/slides/techtalks/Hahn-VPlan-StatusUpdateAndRoadmap.pdf> Accessed: 2024-11-19.

- [3] Chris Lattner and Vikram Adve. 2004. LLVM: A Compilation Framework for Lifelong Program Analysis & Transformation. In *Proceedings of the International Symposium on Code Generation and Optimization: Feedback-Directed and Runtime Optimization (CGO '04)*. IEEE Computer Society, USA, 75.
- [4] Ashutosh Nema and Anupama Rasale. 2023. Improving Vectorization for Loops with Control Flow. <https://llvm.org/devmtg/2023-05/slides/QuickTalks-May10/05-EuroLLVM23%20-%20Improving%20Vectorization%20for%20Loops%20with%20Control%20Flow.pdf> Accessed: 2024-11-20.
- [5] Rouzbeh Paktinatkeleshteri, João P. L de Carvalho, Ehsan Amiri, and J. Nelson Amaral. 2023. Efficient Auto-Vectorization for Control-flow Dependent Loops through Data Permutation. In *Proceedings of the 33rd Annual International Conference on Computer Science and Software Engineering (CASCON '23)*. IBM Corp., USA, 74–83.
- [6] Wyatt Praharenka, David Pankratz, João P. L. De Carvalho, Ehsan Amiri, and José Nelson Amaral. 2022. Vectorizing divergent control flow with active-lane consolidation on long-vector architectures. *Journal of Supercomputing* 78, 10 (July 2022), 12553–12588. <https://doi.org/10.1007/s11227-022-04359-w>
- [7] Gil Rapaport and Ayal Zaks. 2017. Introducing VPlan to the Loop Vectorizer. https://llvm.org/devmtg/2017-03/assets/slides/introducing_vplan_to_the_loop_vectorizer.pdf Accessed: 2024-11-16.
- [8] Hideki Saito and Intel Vectorizer Team. 2016. Extending LoopVectorizer towards supporting OpenMP4.5 SIMD and outer loop auto-vectorization. <https://llvm.org/devmtg/2016-11/Slides/Saito-NextLevelLLVMLoopVectorizer.pdf> Accessed: 2024-11-18.
- [9] Jaewook Shin. 2007. Introducing Control Flow into Vectorized Code. In *Proceedings of the 16th International Conference on Parallel Architecture and Compilation Techniques (PACT '07)*. IEEE Computer Society, USA, 280–291.
- [10] LLVM Team. 2021. Auto-Vectorization in LLVM. <https://llvm.org/docs/Vectorizers.html> Accessed: 2024-11-18.
- [11] LLVM Team. 2024. Vectorization Plan. <https://llvm.org/docs/VectorizationPlan.html> Accessed: 2024-11-18.