Auto-Vectorization with GCC

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HPAC
High Performance and Automatic Computing

Seminar on Code-Generation

Outline

1. Introduction
   - What Is Vectorization
   - What Are The Challenges
2. Structure Of GCC
3. Vectorization
4. Code Generation & Algorithm
5. Summary

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What Is Vectorization

- SIMD: Single Instruction Multiple Data
- Most modern CPUs have SIMD vector registers of mostly 8 to 16 bytes
- Check support on UNIX (Intel/AMD):
  `cat /proc/cpuinfo | grep -E '\s(sse|mmx)\s'`

Definition

Vectorization is the rewriting of loops into vector instructions.
Notation: `a[i:j]` = Elements between index i and j (including).

Challenges

- Memory references must (mostly) be consecutive
- Memory must be aligned to natural vector size boundary
- Number of iterations must be countable
- Data Dependences
- Semantics of the vectorized program must be identical to the original program

Example

```
for (int i=1; i<5; i++)
{
  a[i] = a[i-1] + b[i];    // S1
}
```

Assume a = [1,2,3,4,5] and b = [5,4,3,2,1].

- Sequential: a = [1,5,8,10,11]
- Vectorized: a = [1,5,5,5,5]

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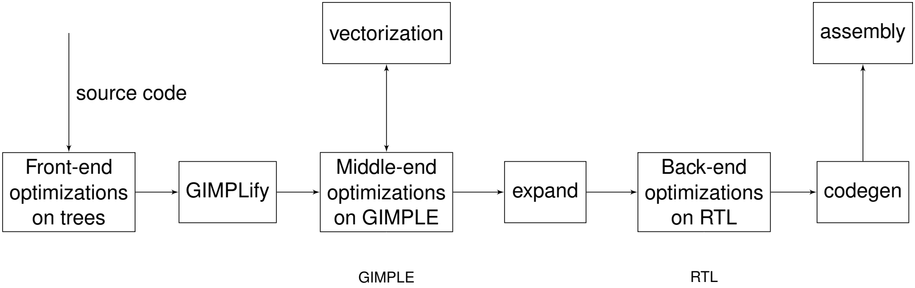
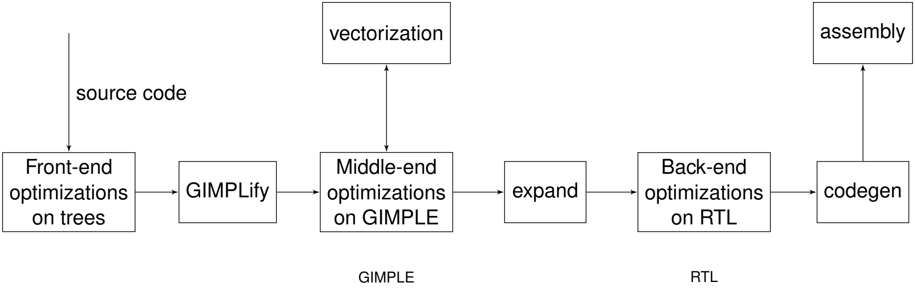
Structure Of GCC



- Vector instructions are platform dependent
- Different processors have different SIMD instruction sets
- When built GCC uses machine description file to store which operations are available
- Intermediate Languages (IL): RTL (Register Transfer Language)
- IL: GIMPLE

Structure Of GCC



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Overview Vectorization Steps

Analyze...

- loop form: exit condition, control-flow, ...
- memory references: compute function that describes memory reference modifications
- scalar dependence cycles
- data reference access patterns
- data reference alignment
- data reference dependences
- Determine *VF* (Vectorization Factor)

Overview Vectorization Steps

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Scalar Dependences

- Use of scalar variables (no arrays, pointers)
- Example: Reduction

Example

```
for (i=0; i<N; i++)
{
  sum += A[i];
}
```

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Scalar Dependences: Reduction

Example

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for (i=0; i<N; i++)
{
  sum += A[i];
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```

- Intel Core 2Duo B950 $\rightarrow VF = 4$
- $N = 1024$, 256 partial sums

Access Patterns

- Most SIMD instruction sets require consecutive memory access
- Otherwise permutations on data is needed
- Some SIMD instruction sets support certain access patterns (e.g. odd/even for complex numbers)
- Costs of permutations are critical to the worth of the vectorization

Example

```
for (i=0; i<N; i++)
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  A[i*2] = x;
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Alignment

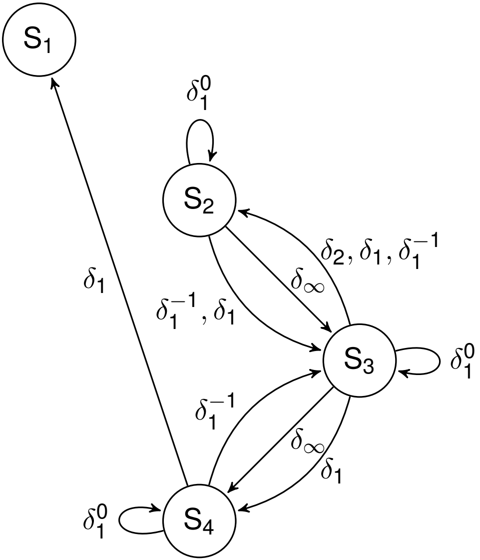
Access on an unaligned memory location is needed.

Target platform needs at least one capability:

- memory read/write to unaligned memory location
- general vector shuffling ability
- specialized alignment support

Most SIMD platforms load VS bytes from closest previous aligned address (e.g. AltiVec, Alpha).

Data Dependences



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Vectorization Algorithm I

```
for (i=1; i<=100; i++) {
  X[i] = Y[i] + 10;          // S1
  for (j=1; j<=100; j++) {
    B[j] = A[j][N];          // S2
    for (k=1; k<=100; k++) {
      A[j+1][k] = B[j] + C[j][k] // S3
    }
    Y[i+j] = A[j+1][N]       // S4
  }
}
```

- codegen(R,k,D), R region, k min nesting level, D dependence graph
- Base for gcc's vectorization procedure

Vectorization Algorithm I

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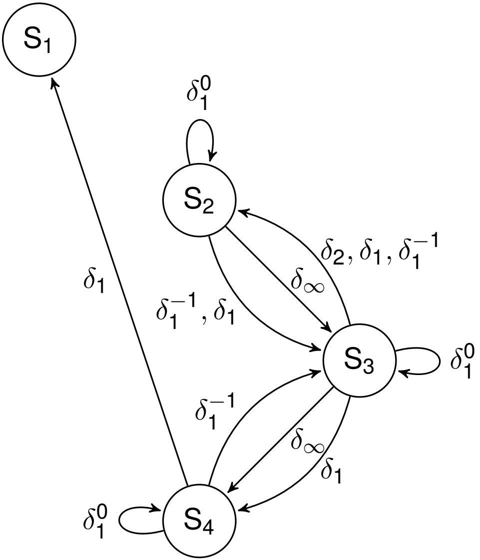
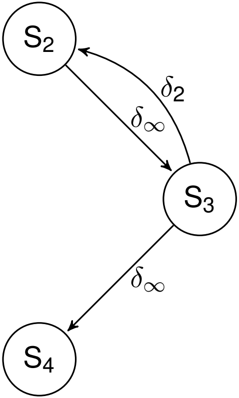
Vectorization Algorithm II



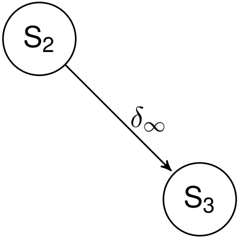
Vectorization Algorithm III

```
for (i=1; i<=100; i++) {
  codegen({S2,S3,S4},2,D2)
}
X[1:100] = Y[1:100] + 10;
```



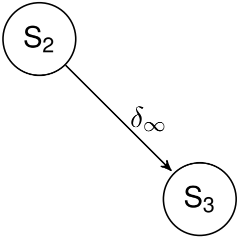
Vectorization Algorithm IV

```
for (i=1; i<=100; i++) {
  for (j=1; j<=100; j++) {
    codegen({S2,S3},3,D3)
  }
  Y[i+1:i+100] = A[2:101][N];
}
X[1:100] = Y[1:100] + 10;
```

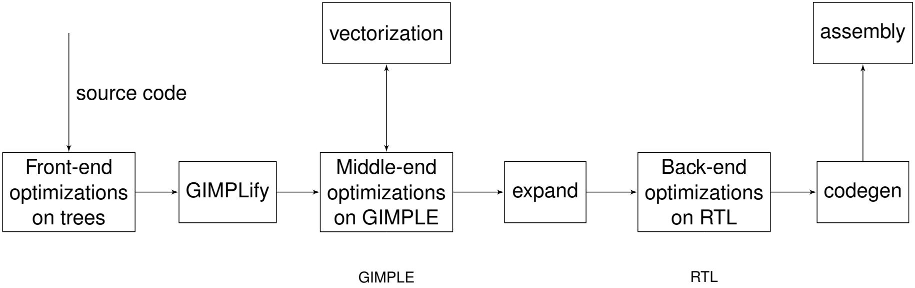


Vectorization Algorithm V

```
for (i=1; i<=100; i++) {
  for (j=1; j<=100; j++) {
    B[j] = A[j][N];
    A[j+1][1:100] =
        B[j] + C[j][1:100];
  }
  Y[i+1:i+100] = A[2:101][N];
}
X[1:100] = Y[1:100] + 10;
```



Code Generation



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- data reference alignment
- Still in progress:
  - Cost model
  - MIMD support
  - Enhancement of existing techniques
  - Much more...

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Summary: Speed Enhancement

Compile code like:

```
gcc example.c -o example_vect -O3
```

- /usr/bin/time -f "%E time, %P CPU" ./example
- 0:00.13 time, 97% CPU
- /usr/bin/time -f "%E time, %P CPU" ./example_vect
- 0:00.03 time, 93% CPU

Speed enhancement of factor $\approx 4 \Rightarrow VF = 4$.

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GCC Code

GCC 4.9 Source gcc/tree-vect*

- 31995 well documented LOC
- Introduced on Jan 1st, 2004 in the lno branch
- Initiated by Dorit Nuzman (IBM)

References

Dorit Nuzman, Richard Henderson (2006)
Multi-platform Auto-vectorization
Proceedings of the International Symposium on Code Generation and Optimization CGO '06, 281–294.

Dorit Naishlos (2004)
Autovectorization in GCC

Dorit Nuzman, Ayal Zaks (2006)
Autovectorization in GCC - Two years later
GCC-Summit-Proceedings 2006, 145–158.

Alexandre Eichenberger, Peng Wu, Kevin O'Brien (2004)
Vectorization for SIMD Architectures with Alignment Constraints
Proceedings of the ACM SIGPLAN 2004 Conference on Programming Language Design and Implementation, 82–93.

Kennedy, Ken and Allen, John R (2001)
Optimizing compilers for modern architectures: a dependence-based approach