20+ years CFG profile in GCC

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GNU Cauldron 2023, Cambridge
What is CFG profile

**CFG profile** is an annotation of the control flow graph (CFG) by

- Expected branch probabilities
- expected basic block execution counts

Zdeněk Dvořák, J. H., Pavel Nejdedlý, Josef Zlomek: *Infrastructure for Profile Driven Optimizations in GCC Compiler*, April 2002

Profile based optimizations

- Originally an excuse to re-organize GCC backend to use commonized control flow graph module
- Re-organized reg-stack to use CFG in 1998
- Started to work on profile infrastructure in 2000
- School project together with Zdeněk, Josef and Pavel in 2001-2002
- AMD Project in 2002-2003
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GCC in 2000

1. Virtually all optimizations done at RTL form
2. RTL function is a single doubly-linked list of statements (no CFG!)
3. Few optimization passes built and used their own CFG (reg-stack, register allocator, Haifa scheduler, dead code elimination, ...)
4. Instruction-level notes used to represent information about loops, libcalls, debug info, ...

Richard Henderson did initial work on generalizing `flow.c` to general CFG infrastructure shared by multiple passes.
Two forms of profile

1. Edge profiling
   - `-fprofile-generate` and `-fprofile-use`
   - Originally by James Wilson, Cygnus, 1990

2. Static profile estimation
   - `-fguess-branch-probability`
   - Originally by Jason Eckhart & Stan Cox, Cygnus, 2000
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3. **Value profiling**
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   - Added by Zdeněk Dvořák in 2003

4. **Auto-FDO (based on low overhead profiling)**
   - `fauto-profile`
   - Contributed by Google in 2014, now maintained by Eugene Rozenfeld

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Original design

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In 2000, as part of work on improving Itanium, branch probability and execution count notes was added to RTL to enable basic block reordering pass.

Static profile represented as:
1. probabilities of edges (in range 0...10000) and
2. frequencies of basic blocks (integers in range 0...10000)

Profile feedback (edge profile) represented as:
1. execution counts of edges (64bit integers)
2. execution counts of basic blocks (64bit integers)

Value profile was read and immediately used for code transformations.

Most work was involved in redesigning existing passes to maintain and use CFG.
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We decided to take this as an excuse to introduce persistent CFG as part of the RTL IL.

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### Static profile estimation

#### heuristics

<table>
<thead>
<tr>
<th>Heuristics</th>
<th>Hitrate</th>
<th>Perfect Hitrate</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>69.74%</td>
<td>80.61%</td>
<td>100.0%</td>
</tr>
<tr>
<td>First match</td>
<td>77.81%</td>
<td>78.31%</td>
<td>69.0%</td>
</tr>
<tr>
<td>No prediction</td>
<td>33.65%</td>
<td>85.08%</td>
<td>15.6%</td>
</tr>
<tr>
<td>DS theory</td>
<td>70.14%</td>
<td>86.40%</td>
<td>15.4%</td>
</tr>
</tbody>
</table>

#### First match:

<table>
<thead>
<tr>
<th>Heuristics</th>
<th>Hitrate</th>
<th>Perfect Hitrate</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop iterations</td>
<td>67.99%</td>
<td>67.99%</td>
<td>39.1%</td>
</tr>
<tr>
<td>Guessed loop iterations</td>
<td>91.73%</td>
<td>92.49%</td>
<td>23.2%</td>
</tr>
<tr>
<td>Loop exit</td>
<td>85.36%</td>
<td>87.83%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Noreturn call</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Fortran loop preheader</td>
<td>99.81%</td>
<td>99.88%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Extra loop exit</td>
<td>82.80%</td>
<td>88.17%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Loop iv compare</td>
<td>52.06%</td>
<td>52.15%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fortran overflow</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fortran fail alloc</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Loop guard with recursion</td>
<td>17.17%</td>
<td>93.91%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

#### Dempster–Shaffer (DS) theory:

<table>
<thead>
<tr>
<th>Heuristics</th>
<th>Hitrate</th>
<th>Perfect Hitrate</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opcode values nonequal (on trees)</td>
<td>67.63%</td>
<td>81.38%</td>
<td>7.2%</td>
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<tr>
<td>Call</td>
<td>67.26%</td>
<td>92.26%</td>
<td>3.3%</td>
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<tr>
<td>Early return (on trees)</td>
<td>54.39%</td>
<td>86.51%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Opcode values positive (on trees)</td>
<td>64.55%</td>
<td>90.39%</td>
<td>1.7%</td>
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<tr>
<td>Pointer (on trees)</td>
<td>69.59%</td>
<td>87.18%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Continue</td>
<td>66.66%</td>
<td>82.85%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Loop guard</td>
<td>61.88%</td>
<td>88.38%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Guess loop iv compare</td>
<td>97.75%</td>
<td>97.79%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Null return</td>
<td>91.47%</td>
<td>93.08%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Negative return</td>
<td>97.94%</td>
<td>99.23%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Const return</td>
<td>69.39%</td>
<td>87.09%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Loop exit with recursion</td>
<td>72.17%</td>
<td>92.33%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Recursive call</td>
<td>75.19%</td>
<td>76.33%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fortran repeated allocation/deallocation</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fortran zero-sized array</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0.0%</td>
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20+ years CFG profile in GCC
Consumers of the profile information

1. Basic-block reordering pass
2. Code alignment (function/loop/jump target alignment)
3. Register allocation (to spill on cold paths)
4. Loop optimizer (to determine unrolling and peeling factors)
5. Loop array prefetching
6. Tracer (new pass doing tail duplication over common paths)
7. Cold code discovery (optimize cold regions for size)
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7. Cold code discovery (optimize cold regions for size)
8. Interprocedural optimizations: Inliner, function cloning
9. Function partitioning
10. Function splitting
11. Higher-level loop optimizations
12. Profile is useful in handling various side cases (code sinking, PRE, . . .)

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Results in 2002

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20+ years CFG profile in GCC
Results in 2023

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20+ years CFG profile in GCC
Persistent loop information

GCC was also updated to keep persistent information about the loop structure. We keep the following info:

1. Upper bound on number of iterations
2. Likely upper bound on number of iterations
3. Expected number of iterations
4. Is loop known to be finite?
5. Force/enable vectorization flag
6. Intended unrolling factor
7. ...

Loop structures are linked with header basic blocks:

1. Code duplication code should mind updating loop structure
2. Some passes move loop headers and should also update the links
   (otherwise loop is lost & rediscovered and all annotations are forgotten)

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2017 CFG profile revamp

C++ data-types replacing frequencies, probabilities and counts:

1. `profile_probability`, 32 bits stored in CFG edges:
   1. 29 bits of fixed point probability (value in 0...1)
   2. 3 bits quality information:
      1. UNINITIALIZED_PROFILE
      2. GUESSED
      3. AFDO (value used to be known precisely but we duplicated code and it may not be representative anymore)
      4. PRECISE

2. `profile_count`, 64 bits stored in CFG basic blocks and callgraph:
   1. 61 bits fixed point execution count
   2. 3 bits quality information with few extra options:
      1. GESSED_LOCAL (value is known only within single function and is relative to the entry block count)
      2. GESSED_GLOBAL0 (function was never executed in train run, but we have local estimate)

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profile_probability supports:

Predefined values:

- never (0 precise), always (1 precise),
- even (0.5 guessed),
- likely (0.8 guessed), unlikely (0.2 guessed)
- very_likely (0.998 guessed), very_unlikely (0.002)
- uninitialized
- ...

Basic operations +, −, ∗, /, pow, sqrt with obvious meaning.

All capping and propagating quality info.

Comparisons <, >, =, < =, > = are three-way and returns false if unknown.

Conversion to sreal; conversion to original REG_BR_PROB_BASE fixpoint is deprecated.

Probability can be applied to profile_count

Probability can be scaled by fractions of two profile_count or gcov_type

reliable_p predicate

Dumping, debug output and LTO streaming...
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5. Probability can be applied to `profile_count`

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7. `reliable_p` predicate

8. Dumping, debug output and LTO streaming

9. ...
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Dumping, debug output and LTO streaming

...
Value histograms are attached to statements using on-side hash similar way as we do with EH regions.

1. First execution time profiling
   (for code reordering)

2. Indirect call profiling
   (represented in callgraph to aid inlining)

3. Division/modulo by constant or power of 2 transformation

4. String operation buffer size profiling
Profile maintenance

1. Profile info is estimated or read in early and needs to be maintained across the whole optimization pipeline.

2. Low-level API (edge redirection, BB creation, ...) has no info needed to determine profile.

3. Sometimes profile becomes incoherent as a result of optimizations:

```c
int foo (int a)
{
    if (a) // 0.5 probability before inlining
        bar ();
}
main()
{
    foo (0); // probability 0 after inline
    foo (1); // probability 1 after inline
}
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Every pass is responsible to cleanup its own mess!
2023 is a year of profile fixes for me

Our LNT tester tracks profile quality building tramp3d

https://lnt.opensuse.org/db_default/v4/CPP/latest_runs_report counts section

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Progress so far

- vectorizer
- loop header copying
- loop splitting
- jump threading
- loop peeling
- loop versioning
- loop unrolling
- branch prediction
- profile datatructures
- DCE
- reassoc
- sreal
- loop invariant motion
- loop distribution
- Patches in various stage of baking

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No RTL yet

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Hmmer with `-Ofast -flto -march=native`

Legend

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test</th>
<th>Type</th>
</tr>
</thead>
</table>
Please mind the profile!

1. Use `blocks-details dump` flags to see information about profile mismatches.
2. If you spot some after your transformation try to see if it is carried in or needs to be fixed.
3. `--fprofile-report` can be used to get overall data about profile quality.
4. Add tests checking profile updates searching for Invalid sum.
5. Try to think of side cases:
   1. What happens when profile is missing
   2. What happens when profile is inconsistent on the input (try to minimize chance of spreading the error further)
   3. ...
6. Transformations affecting CFG needs to update profile (even if you just update conditional to constant 0 or 1 and let `cfgcleanup` do the work)
7. Transformations affecting loop headers or iteration counts needs to update loop structure.

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<table>
<thead>
<tr>
<th>pass</th>
<th>profile mismatches</th>
<th>size</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>86t inline</td>
<td>+44649708141</td>
<td>+33.1%</td>
<td>-10.3%</td>
</tr>
<tr>
<td>103t ccpr</td>
<td>+48243471353</td>
<td>-0.5%</td>
<td>-0.6%</td>
</tr>
<tr>
<td>108t cunrolli</td>
<td>-5321807717</td>
<td>-0.0%</td>
<td>-0.9%</td>
</tr>
<tr>
<td>111t forwprop</td>
<td>+6468</td>
<td>-0.1%</td>
<td>-1.1%</td>
</tr>
<tr>
<td>114t fre</td>
<td>+24027489258</td>
<td>-1.2%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>116t threadfull</td>
<td>+384565874522</td>
<td>-0.1%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>117t vrp</td>
<td>+33600542417</td>
<td>-4.7%</td>
<td>-0.5%</td>
</tr>
<tr>
<td>118t dse</td>
<td>-1256513433</td>
<td>-0.3%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>119t dce</td>
<td>-3122885968</td>
<td>-0.1%</td>
<td>-0.4%</td>
</tr>
<tr>
<td>122t cselim</td>
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</table>
Please use the profile in your passes

1. Use `optimize_*_for_speed` and `optimize_*_for_size`.
   (* is one of function, bb, insn, loop, loop_nest)

   `optimize_*_for_size` is now a two-state predicate. Returned value is `optimize_size_level` enum:
   0: OPTIMIZE_SIZE_NO (optimize for speed, this may be a hot part of the program)
   1: OPTIMIZE_SIZE_BALANCED (this is likely not a hot part of the program but evidence is low; avoid bloat but do not do extreme tradeoffs)
   2: OPTIMIZE_SIZE_MAX (do everything possible to reduce code size, a lot of target specific work is needed here)

4. Use persistent loop info in loop transformations. Most loop transforms are miss for loops iterating 0 or very few times.

4. Use probabilities and counts to guide decisions about code paths.

J. Hubička 20+ years CFG profile in GCC
Please use the profile in your passes

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J. Hubička 20+ years CFG profile in GCC
Future plans

1. Fix remaining bugs
2. More test coverage (302 testcases in trunk compared to 76 in GCC 13)
3. Track more Int testcases
4. Integrate histogram profiling code (see Ondra’s talk!)
5. Make vectorizer to use histogram profiles
6. Set up auto-FDO performance testing
7. Enable partitioning for more targets
8. Profile feedback at LTO linktime (no need to recompile)
9. . .
Thank you!