Go Execution Tracer

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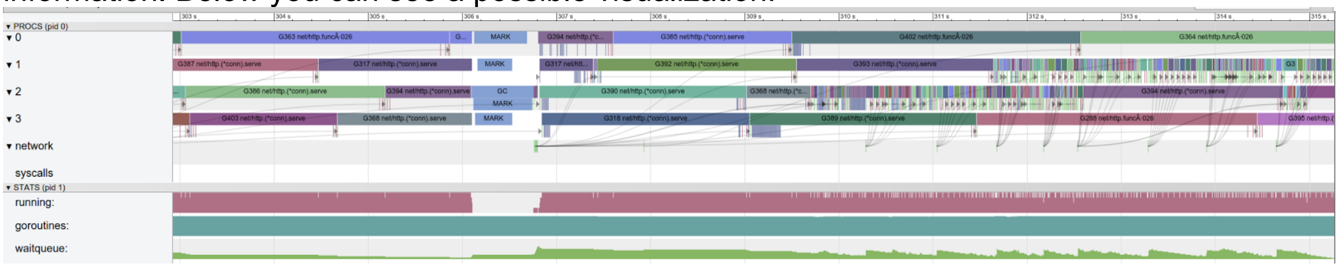
Abstract

Go has a number of profiling tools -- CPU, memory, blocking profilers; GC and scheduler tracers and heap dumper. However, profilers provide only aggregate information, for example, how much memory in total was allocated at this source line. Tracers provide very shallow information. Heap dumper gives detailed per-object information about heap contents. But there is nothing that gives detailed non-aggregate information about program execution -- what goroutines do execute when? for how long? when do they block? where? who does unblock them? how does GC affect execution of individual goroutines?
The goal of the tracer is to be the tool that can answer these questions.

High-level Overview

A Go program with tracing capability can write trace of interesting events to a file. The capability is compiled into all programs always, and is enabled on demand -- when tracing is disabled it has minimal runtime overhead. That is, the trace can be obtained from a server in production serving live traffic.
The trace contains events related to goroutine scheduling: a goroutine starts executing on a processor, a goroutine blocks on a synchronization primitive, a goroutine creates or unblocks another goroutine; network-related events: a goroutine blocks on network IO, a goroutine is unblocked on network IO; syscalls-related events: a goroutine enters into syscall, a goroutine returns from syscall; garbage-collector-related events: GC start/stop, concurrent sweep start/stop; and user events. Here and below by "processor" I mean a logical processor, unit of GOMAXPROCS. Each event contains event id, a precise timestamp, OS thread id, processor id, goroutine id, stack trace and other relevant information (e.g. unblocked goroutine id).
Once a trace is obtained, it can be visualized and/or processed to extract various types of interesting information. Below you can see a possible visualization:



(to zoom: right-click, then select 'Open image in new tab')
Post-processing of the trace can give several useful views:

- a better blocking profiler (go test -blockprofile), it can show not just a sum of blocking time per stack, but a histogram of blocking times with an ability to drill into outliners.
- a better scheduler tracer (GODEBUG=schedtrace), as it can show and explain exact sizes of workqueues, work stealing, thread spinning, number of threads in syscalls, etc.
- what is the min/max/average/histogram IO time for this particular stack?
- what is blocking time and scheduling latency (time between a goroutine was unblocked and actually scheduled for execution) for this select?
- or what is the duration of goroutines created in this place, and then you can look at the outliner in the visual trace to understand why it takes longer than others.

Interfaces

As other profiles, execution trace can be collected in 3 ways:

1. Using `go test -trace` flag. This is intended to be used with a single benchmark:

```
$ go test -trace=/tmp/trace -run=nothing -bench=MyBenchmark -cpu=8
```

2. Using net/http/pprof handler registered at `/debug/pprof/trace`. The handler accepts `seconds` parameter to control duration of the trace.
3. Programmatically using interface exposed from `runtime/pprof` package:

```
package pprof
func StartTrace(fd uintptr) error
func StopTrace()
```

Runtime/pprof package also exposes a set of functions for emission of user events:

```
package pprof
func TraceEvent(id string)
func TraceScopeStart(id string)
func TraceScopeEnd(id string)
```

Trace Format

A parallel Go program can generate up to hundreds thousands events per second. So the trace is written in a compact binary format:

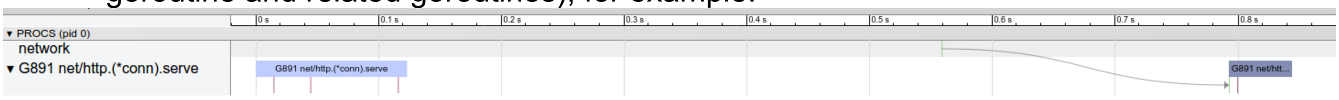
```
Trace           = "gotrace/x00" Version {Event} .
Event          = EventProcStart | EventProcStop | EventFreq | EventStack |
EventGomaxprocs | EventGCStart | EventGCDone | EventGCScanStart |
EventGCScanDone | EventGCSweepStart | EventGCSweepDone | EventGoCreate |
EventGoStart | EventGoEnd | EventGoStop | EventGoYield | EventGoPreempt |
EventGoSleep | EventGoBlock | EventGoBlockSend | EventGoBlockRecv |
EventGoBlockSelect | EventGoBlockSync | EventGoBlockCond | EventGoBlockNet
| EventGoUnblock | EventGoSysCall | EventGoSysExit | EventGoSysBlock |
EventUser | EventUserStart | EventUserEnd .
EventProcStart  = "\x00" ProcID MachineID Timestamp .
EventProcStop   = "\x01" TimeDiff .
EventFreq       = "\x02" Frequency .
EventStack      = "\x03" StackID StackLen {PC} .
EventGomaxprocs = "\x04" TimeDiff Procs .
EventGCStart    = "\x05" TimeDiff StackID .
EventGCDone     = "\x06" TimeDiff .
EventGCScanStart= "\x07" TimeDiff .
EventGCScanDone = "\x08" TimeDiff .
EventGCSweepStart  = "\x09" TimeDiff StackID .
EventGCSweepDone= "\x0a" TimeDiff .
EventGoCreate   = "\x0b" TimeDiff GoID PC StackID .
EventGoStart    = "\x0c" TimeDiff GoID .
EventGoEnd      = "\x0d" TimeDiff .
EventGoStop     = "\x0e" TimeDiff StackID .
EventGoYield    = "\x0f" TimeDiff StackID .
EventGoPreempt  = "\x10" TimeDiff StackID .
EventGoSleep    = "\x11" TimeDiff StackID .
EventGoBlock    = "\x12" TimeDiff StackID .
EventGoBlockSend= "\x13" TimeDiff StackID .
EventGoBlockRecv= "\x14" TimeDiff StackID .
EventGoBlockSelect = "\x15" TimeDiff StackID .
EventGoBlockSync= "\x16" TimeDiff StackID .
EventGoBlockCond= "\x17" TimeDiff StackID .
EventGoBlockNet = "\x18" TimeDiff StackID .
EventGoUnblock  = "\x19" TimeDiff GoID StackID .
EventGoSysCall  = "\x1a" TimeDiff StackID .
EventGoSysExit  = "\x1b" TimeDiff GoID .
EventGoSysBlock = "\x1c" TimeDiff .
```

```
EventUser        = "\x1d" TimeDiff StackID MsgLen Msg .
EventUserStart   = "\x1e" TimeDiff StackID MsgLen Msg .
EventUserEnd     = "\x1f" TimeDiff StackID MsgLen Msg .
```

ProcID, MachineID, GoID, Timestamp, TimeDiff, Frequency, StackID, StackLen, PC, Procs, MsgLen are encoded in Unsigned [Little Endian Base 128](#) (LEB128) encoding. Msg is encoded in utf-8.
Each P collects events in a per-P buffer, the buffer starts with EventProcStart event which contains full Timestamp. The rest of the events in the batch contain TimeDiff which is diff from the previous event (this allows to keep most of the TimeDiff's small and so encoded in fewer bytes). Timestamps has nanosecond precision and are collected with RDTSC. ProcID and MachineID for most events are implied by the previous EventProcStart event. Similarly, GoID, current goroutine id, is implied by the previous EventGoStart event.
EventFreq is written once per trace and denotes the resolution of timestamps in the trace.
EventStack maps StackID to actual stack trace (array of PCs).
EventUser/EventUserStart/EventUserEnd are emitted by user code and allow to denote instant events and duration events, respectively.
The rest of the events describe goroutine scheduling and GC. E.g. EventGoBlockRecv denotes blocking on chan recv; EventGoUnblock denotes unblocking of a goroutine by another goroutine, etc.

User Interface

The user facing part consists of a package that reads, decodes, validates and restores implicit information in the trace, and a set of tools invoked by user. The initial set of options is:
- look at the whole trace (see other screenshots)
- look at the trace for particular goroutine (the tool extracts events only for the requested goroutine and related goroutines), for example:



- look at the list of goroutines and their aggregate characteristics (total time, execution time, time spent in mutex blocking, time spent in network blocking, time spent waiting for GC, etc) (see the screenshot in the Evaluation section)

For trace visualisation it's proposed to use Chromium Trace Viewer (https://github.com/google/trace-viewer). All screenshots in this doc use it.

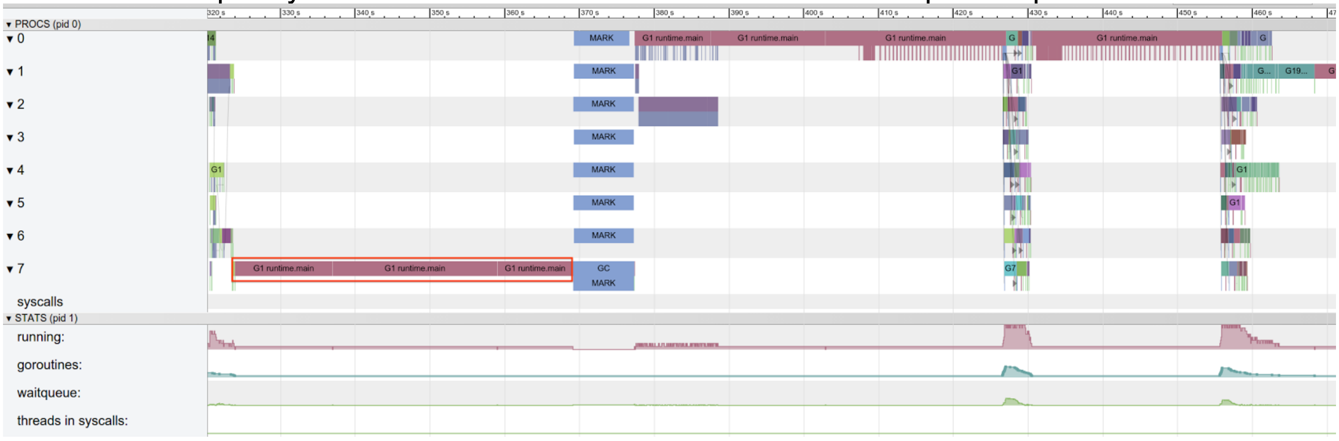
Evaluation

This functionality is implemented in the following CL:
https://codereview.appspot.com/146920043
There are some minor differences and non-implemented parts. For example, numbers are encoded as uint32 rather than in LEB128; user events are not implemented. But the overall idea matches what's described here.
The change adds ~150 LOC to runtime for event tracking. Most of the added code is trivial like:

```
if traceEnabled {
        traceGCStart()
}
```

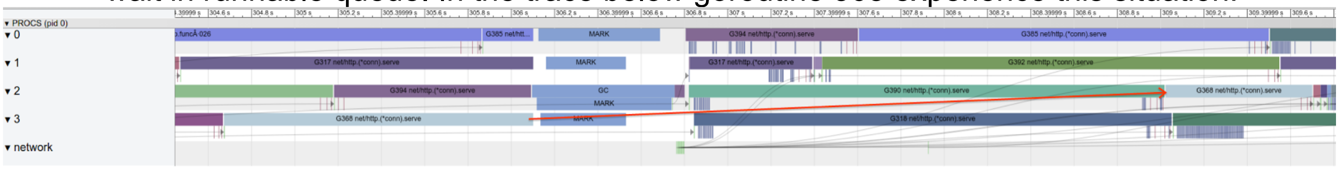
The only non-trivial aspect is detecting when runtime considers that a syscall blocks (and it's also the bulk of the code).
Plus ~550 LOC in a separate file for trace encoding, writing, starting and stopping.
Performance impact when tracing is not enabled is within noise -- global flag check on goroutine creation, blocking, unblocking, etc.
Performance impact when enabled is ~35% on net/http:BenchmarkClientServerParallelTLS4. 75% of the overhead is stack unwinding.
The average size of an event is ~9 bytes in this implementation. With the LEB128 encoding it should be reduced to roughly 5 bytes/event. net/http:BenchmarkServerParallelTLS4 benchmark writes trace at ~1 MB/second speed. That should be reduced to ~0.5 MB/seconds speed with the LEB128 encoding.
We were able to identify 4 issues in Go programs using the functionality:

1. Insufficient parallelization in go.types. Type checking of packages happens sequentially. It's very clear from the trace below. The trace allows to understand what exactly is sequential and also to quickly estimate how much time is wasted in the sequential phase:



(to zoom: right-click, then select 'Open image in new tab')

2. Latency issue due to GC. When GC stops a goroutine, it is put at the tail of FIFO runnable queue. So the unlucky goroutine experience double penalty: a pause due to GC + another wait in runnable queue. In the trace below goroutine 368 experience this situation:



(to zoom: right-click, then select 'Open image in new tab')

3. Using the goroutine summary page we identified mutex contention in two different servers. The view compares different goroutines with the same starting function. It makes it easy to compare the fastest goroutines with the slowest goroutines and identify source of slowdown -- whether it's higher computational requirements, network blocking, mutex blocking or GC pauses. Then you can look at traces for individual goroutines to identify exact place of blocking, etc:

Goroutine	Total time, ns	Execution time, ns	Network wait time, ns	Sync block time, ns	Blocking syscall time, ns	Scheduler wait time, ns	GC sweeping time, ns	GC pause time, ns
2061	1968957401	161030671	1412923912	62525758	182505982	315532123	4480793	301398423
1703	1968942069	168190480	1428379219	46941216	56556046	293617744	4916094	301398423
2060	1968932203	169932024	1448261328	42781434	741185	290411333	5708430	301398423
2059	1968930257	167425828	1445732203	41652201	258514655	285764041	8437614	301398423
1705	1968925058	167427060	1457823944	34551861	87093173	280492314	4565951	301398423
1704	1968923178	163245226	1450678023	29541669	34042757	299498894	5254743	301398423
1708	1968909970	168102029	1425027735	50701855	4442242	302321605	6225867	301398423
2062	1968899440	168014905	1433939459	33864212	19212358	302989702	5353769	301398423
1706	1968898069	166485266	1453897279	33423555	286800819	295255432	5105480	301398423
1709	1968873226	163979186	1424909657	45681702	41906320	308331214	4599526	301398423
1707	1968871876	167878931	1436750072	40072248	95010847	292749009	5638829	301398423
1710	1968848006	166829895	1432001030	38190527	146944575	295927164	4953258	301398423
1711	1968816150	172636612	1444261019	42025871	102694246	285577411	4967887	301398423
2036	1968783917	169144811	1436939955	27271304	56549697	304731219	4577273	301398423
2033	1968782723	168356866	1447027110	36108931	64085651	294845236	4419211	301398423
2034	1968775202	170086310	1443781008	44661230	49352059	283851993	4505020	301398423
1712	1968770357	163070268	1459283038	35569527	521034260	281335372	4011716	301398423
2039	1968754274	162364758	1460781191	27484055	167925366	293129881	5311125	301398423
2035	1968744806	169391900	1430324825	41935124	146921856	301131422	4977321	301398423
2038	1968712109	179314843	1411883314	61270307	286803805	299944041	4945935	301398423
2037	1968701025	179811508	1422095660	50162547	167923530	299772143	5565065	301398423
2040	1968691978	173237749	1444451985	33507221	64032867	287996802	7411379	301398423

(to zoom: right-click, then select 'Open image in new tab')

Usage:

Apply the changelist and build the toolchain. Then, build your program with the toolchain. You have 2 options for trace collection:

1. Run the program with GOTRACE=/tmp/trace env var, then all execution will be traced and the trace written to /tmp/trace.
2. Import net/http/pprof and query /debug/pprof/trace?seconds=5 on the running program. The trace for 5 seconds will be downloaded.

Then, checkout https://github.com/google/trace-viewer which contains trace2html program.

To look at the raw trace run:

$ GOROOT/bin/trace -trace=/tmp/trace.json /your/server/binary /the/trace/you/downloaded

```
$ trace-viewer/trace2html /tmp/trace.json
```

then open "/tmp/trace.html" in your browser.

To look at the pre-processed trace, do:

```
$ PATH=./trace-viewer:$PATH $GOROOT/bin/trace -http=localhost:9876 /your/server/binary /the/trace/you/downloaded
```

This will open a browser window. The page will contain several links:

Goroutines - list of goroutines

IO - stacks where the program blocks on IO

Blocking - stacks where the program blocks on sync primitives and channels

Syscalls - blocking syscalls

Click "Goroutines", then choose an interesting goroutine type (hopefully near top). You will see a list of goroutines with a bunch of characteristics (total time, execution time, blocking time, etc). Then click on various goroutine ids to look at the trace for that particular goroutine -- the goroutine itself will be in the first raw. If you are not familiar with chrome trace viewer, click ? button in the top-right corner.

Note: timestamps are currently off by 1000 in the trace viewer, that is 1 second is actually 1 millisecond.

Here you can download an example of the visualized HTML trace file (6.2MB) to play with locally.