ivy Dynamic Feedback Control
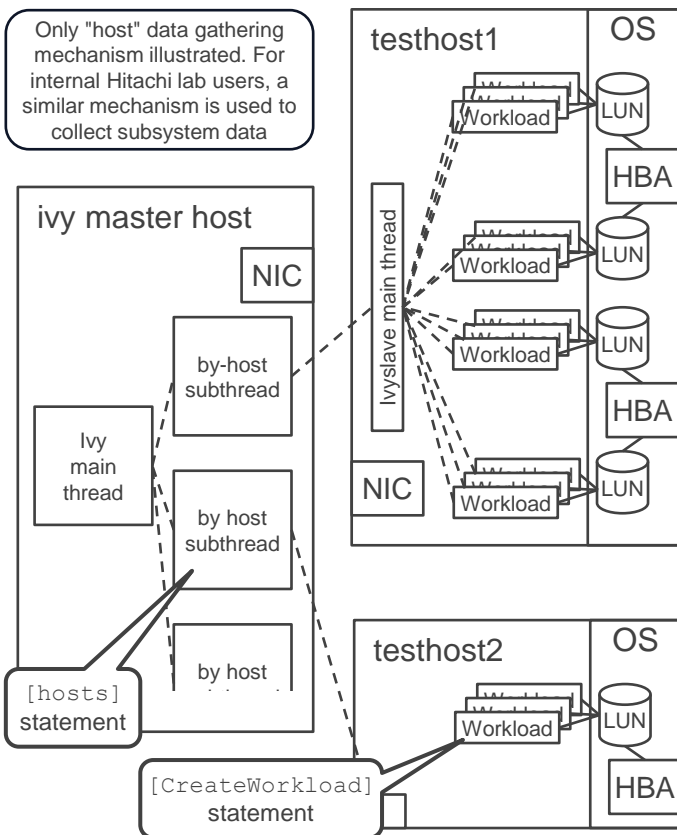
Adaptive PID Loop

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Ivy was designed for dynamic feedback control

Only "host" data gathering mechanism illustrated. For internal Hitachi lab users, a similar mechanism is used to collect subsystem data

ivy master host

NIC

Ivy main thread

by-host subthread

by host subthread

by host

[hosts] statement

[CreateWorkload] statement

testhost1

OS

Workload

LUN

HBA

Ivyslave main thread

Workload

LUN

Workload

LUN

HBA

NIC

Workload

LUN

testhost2

OS

Workload

LUN

HBA

- At the end of every (default 5-second) subinterval, data from each workload thread is rolled up centrally.

- The data for each individual workload is posted multiple times. It is posted exactly once into each "rollup".

  - A rollup instance is a set of workload threads.

  - Each workload thread appears in one instance of every rollup.

  - The "`all`" rollup has one instance "`all=all`" containing all workloads.

- If a Hitachi command device connector is active, subsystem performance data is sent to the master host.

  - The detail by subsystem component is filtered by rollup instance, using the subsystem configuration data to match workloads to their underlying LUNs LDEVs, ports, PGs, MPUs, etc.

  - This by-rollup filtering of subsystem data enables DFC at the granularity of the rollup instance, even for subsystem data.
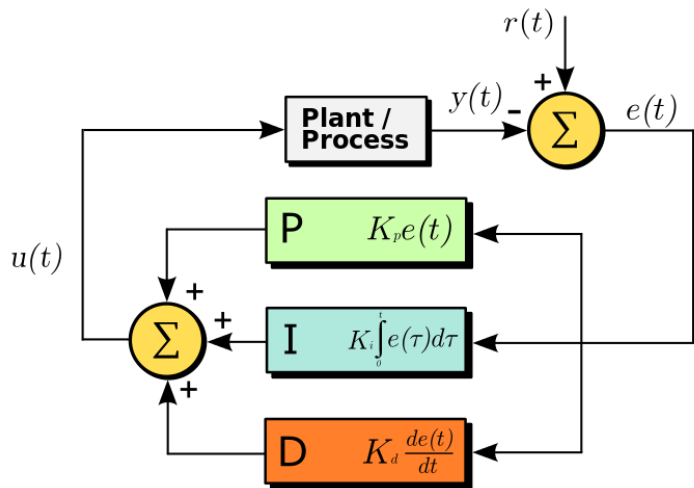
Once host & subsystem data rollups complete
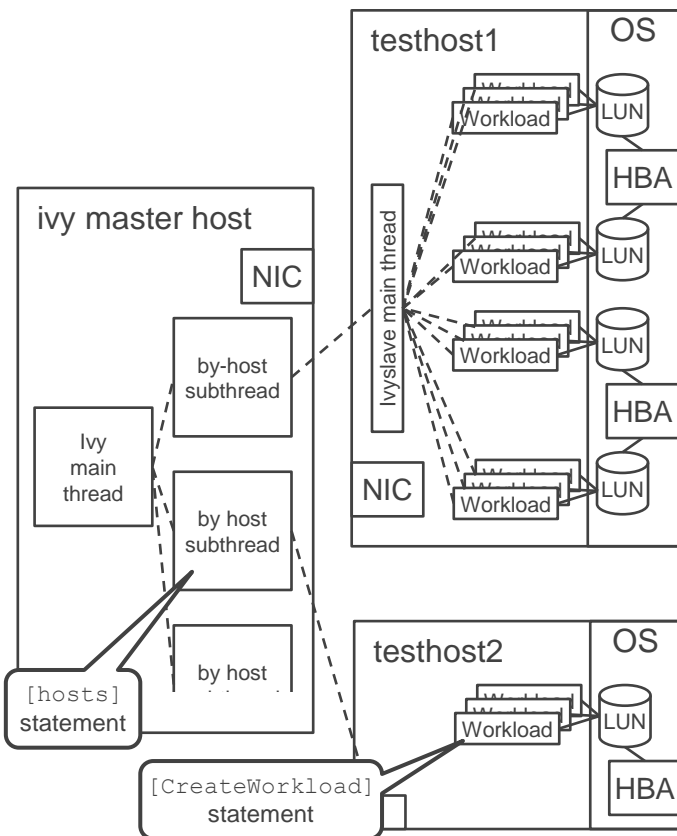
- Examine the rolled up real time host & subsystem data, and decide if any iosequencer parameters need to be adjusted.

- Using the [EditRollup] mechanism, optionally send out iosequencer parameter updates by rollup instance in real time to immediately affect running workload threads.
  - The `DFC=PID` plugin edits IOPS by "focus rollup" instance.

- Decide whether the ivy engine should stop or continue, at the end of the currently running subinterval.
  - `measure = service_time_seconds, accuracy = 1%`

- The ivy engine sends "stop" or "continue" to each ivyslave, which in turn propagates to each workload thread.
  - The "stop" or "continue" must arrive at each running workload thread before it gets to the end of the currently running subinterval.

Ivy engine characteristics

- Workload threads operate driving and harvesting I/Os without ever waiting for their parent ivyslave thread.

  – The ivy engine must have delivered "continue" or "stop" before the end of the subinterval is reached.

  – Workload threads don't communicate with each other.

    – Dedupe uses a statistical method to ensure the right average number of copies are written.

- In order to avoid disturbing any workload thread, ivyslave waits for a short "catnap" after the end of the subinterval to make sure the independently dispatched workload threads have finished posting before ivyslave harvests and sends the posted data to ivymaster.

  – After the catnap is complete, it only takes milliseconds for all the data to roll up centrally.

- Command device collection is timed based on historical latencies for central rolled up "just in time" availability at the end of the subinterval.

- DFC parameter updates take effect immediately when sent out. Propagation is in milliseconds.

Dynamic Feedback Control using a PID Loop

$r(t)$

$y(t)$

$e(t)$

Plant / Process

$u(t)$

Σ

$+$
$-$

P $K_p e(t)$

I $K_i \int_0^t e(\tau)d\tau$

D $K_d \frac{de(t)}{dt}$

Σ
$+$
$+$
$+$

P   is for Proportional
I   is for Integral
D   is for Differential

- Once all the measurement data have been received at the ivy master host at the end of each subinterval, a new IOPS value is calculated and then immediately sent out using the "edit rollup" mechanism to running workload threads.

- The new IOPS is the sum of three things:

  1. "P" times the error signal.

  2. "I" times the cumulative error since the test began

  3. "D" times the rate of change of the error signal

- See http://en.wikipedia.org/wiki/PID_controller

First perform 3 calibration measurements

1. Measure max IOPS   `measure = IOPS, IOPS = max`

    –   This measured max IOPS value is only used to perform steps 2) and 3)

2. Measure the target PID control metric at the lower IOPS limit of the operating range (e.g. measure at 1% of max IOPS).

    –   Later you will specify `low_IOPS =` xxxx, `low_target =` yyyy

3. Measure the PID control metric at upper IOPS limit of the operating range (e.g. measure at 90% of max IOPS).

    –   Later you will specify `high_IOPS =` aaaa, `high_target =` bbbb

-   The `target_value` you specify for the PID loop must be in the range from `low_target` to `high_target`.

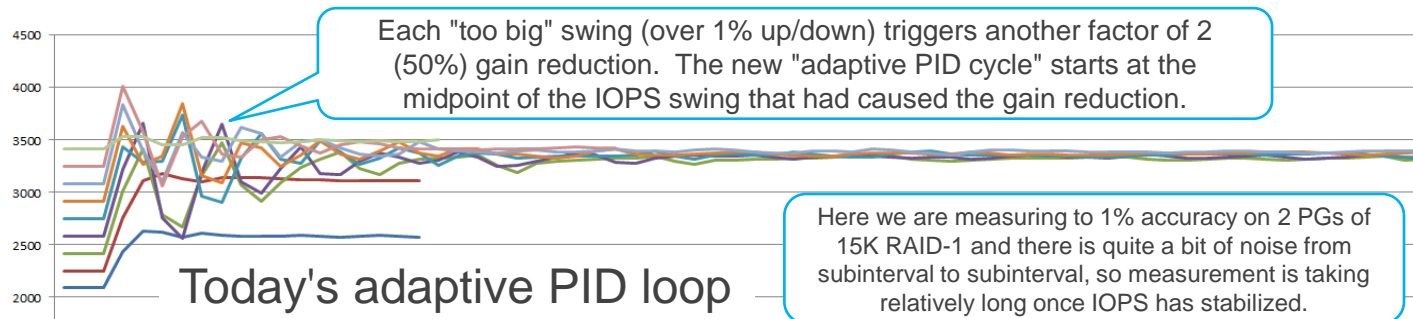-   These measurements are for the total IOPS (`all=all` instance)

Select the "PID control metric"

- Both DFC and the "measure" feature use the same "focus metric"

- ```
  dfc = pid, target_value = 0.001
  dfc = pid, target_value = 50%
  ```

- Often the focus metric is set using one of the "shorthand" settings.
  ```
  measure = service_time_seconds
  measure = response_time_seconds
  measure = MP_core_busy_percent
  measure = PG_busy_percent
  measure = CLPR_WP_percent*
  ```

  * For `CLPR_WP_percent` the current PID loop should work, but it may take a long time before the IOPS settles down.

- The shorthand `measure = IOPS` and `measure = MB_per_second` can't be used as a PID control metric because, obviously, it's the IOPS that is the "input".

Adaptive PID function

- The calibration values `low_IOPS`, `low_target`, `high_IOPS`, and `high_target` are used together with `target_value` to establish starting "ballpark" rough estimated parameters for the PID loop.

  – Starting IOPS.

  – Starting "I parameter, the cumulative error gain.

  – A starting value for the PID loop cumulative error that will yield the desired starting IOPS at the starting gain.

- When the PID loop starts running, an adaptive method is used to adjust the gain to rapidly approach the target PID control metric value, and then settle in and lock on stably.

- Measurement only can start after the last adaptive gain adjustment.

Adaptive behaviour – gain too high

- If an IOPS "swing" up or down is bigger than `"max_ripple"` (default 1%), then the gain is reduced by a factor of `"gain_step"` (default factor of 2) and a new "adaptive PID subinterval cycle" is started.

- Measurement can only begin after all gain adjustments are complete (IOPS swings up and down are smaller than `"max_ripple"`)

Early ivy fixed-gain PID loop

Each "too big" swing (over 1% up/down) triggers another factor of 2 (50%) gain reduction. The new "adaptive PID cycle" starts at the midpoint of the IOPS swing that had caused the gain reduction.

Today's adaptive PID loop

Here we are measuring to 1% accuracy on 2 PGs of 15K RAID-1 and there is quite a bit of noise from subinterval to subinterval, so measurement is taking relatively long once IOPS has stabilized.

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Adaptive behaviour – gain too low

- **If IOPS initially goes continuously in the same direction for more than `max_monotone` subintervals (default 5), gain is increased by the same `gain_step` factor and a new "adaptive PID subinterval cycle" is started.**

Ease of use:

- **`gain_step = 2` works exactly the same as `gain_step = 0.5` or `gain_step = 50%`**

Early ivy fixed-gain PID loop

Hard to tell if you have arrived on target or if it's just moving really slowly.

Gain keeps getting increased until the target value is crossed and IOPS starts moving in the opposite direction. Then the same gain reduction & measurement operates as previously shown.

Adaptive PID loop

The idea here is to keep increasing gain to get to the target more quickly, and then once the target IOPS is crossed, damp the gain down as necessary to stabilize on the target.

gain increase inflection point

Summary of operating `DFC = PID`

- Measure max IOPS

- Measure PID control metric at 1% and at 90% of max IOPS

- `[Go] "measure = service_time_seconds, accuracy_plus_minus = 1%,` `dfc = pid, target_value =` tt`, low_IOPS =` xx`, low_target =` yy`,` `high_IOPS =` aa`, high_target =` bb`"`

- Advanced user options to control adaptive PID (defaults shown)
  - `gain_step = 2, max_ripple = 1%, max_monotone = 5,` `ballpark_seconds = 60, min_IOPS = 10`
    - The "`min_IOPS`" parameter expresses the lowest allowable IOPS setting that the PID loop may send out. This is done so that there will always be a service time measurement.

`adaptive_PID.ivyscript` example

- Start up ivy and create workloads:

```
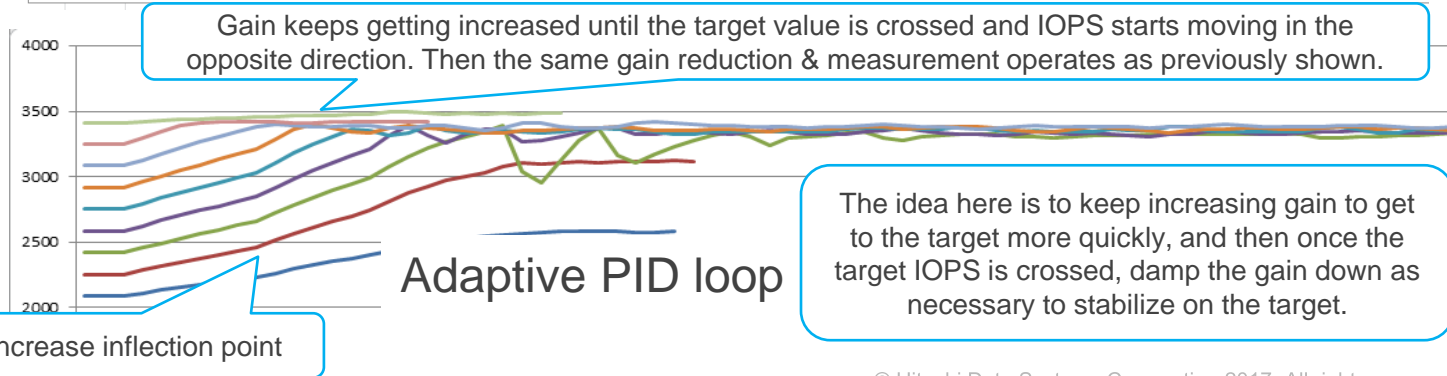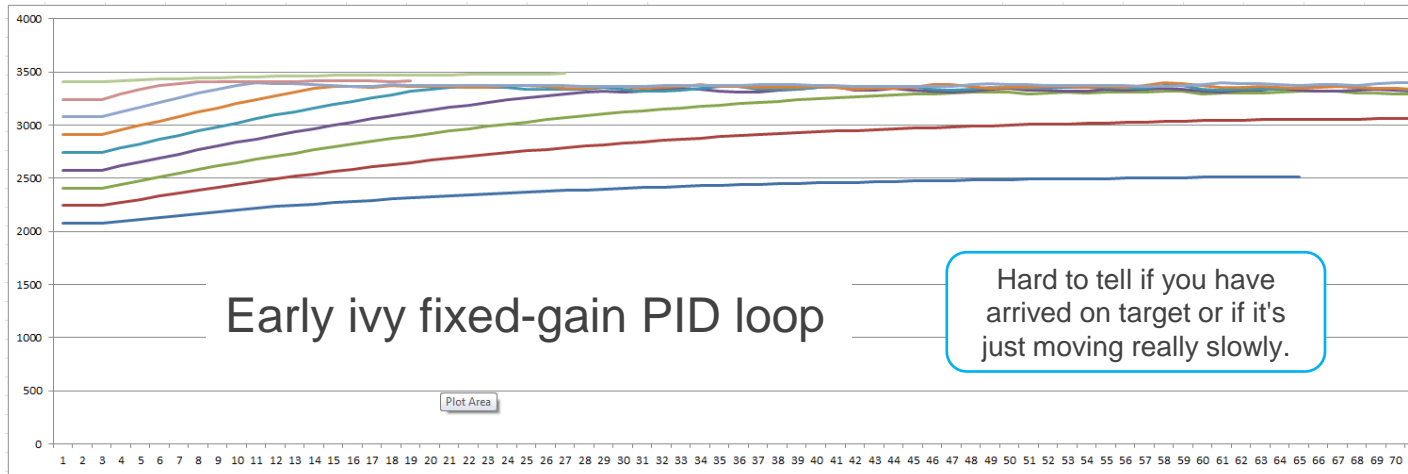[outputFolderRoot] "/some/where/ivyoutput";

double accuracy = 1%;

[hosts] "sun159"
          [select] "serial_number : 83011441";


[CreateWorkload] "steady"
          [select]    "LDEV : [ 0008, 0009 ]"
          [iogenerator] "random_steady"
          [parameters] "fractionRead = 100%, blocksize = 4KiB, IOPS = max, maxtags = 128";
```

`adaptive_PID.ivyscript` example

- **Measure max IOPS:**

```
[Go!] "stepname = \"IOPS = max\", measure = IOPS, accuracy_plus_minus = " + string(accuracy);

// Retrieve the "Overall IOPS" value from the step 0 row of the summary.csv file for the all=all rollup.

string summary_filename = testFolder() + "/all/" + testName() + ".all=all.summary.csv";

set_csvfile(summary_filename);

double max_IOPS = double(csvfile_cell_value(0,"Overall IOPS"));

drop_csvfile(summary_filename);
```

`adaptive_PID.ivyscript` example

- **Measure target metric at 1% of max IOPS:**

```
double low_IOPS = 1% * max_IOPS;

[EditRollup] "all=all" [parameters] "total_IOPS=" + string(low_IOPS);

[Go]  "stepname=\"low_target at 1% of max\", measure = service_time_seconds, timeout_seconds = 600"
  + ", accuracy_plus_minus = " + string(accuracy);

// Retrieve "low_target":

set_csvfile(summary_filename);

string result = last_result();  if ("success" != result)
          { s = "Failed to obtain measurement running at 1% of max IOPS.\n";
            print(s); log(masterlogfile(),s); exit(); }

double low_target_ms = double(csvfile_cell_value(1,"Overall Average Service Time (ms)"));

double low_target = low_target_ms / 1000.0;

drop_csvfile(summary_filename);
```

`adaptive_PID.ivyscript` example

- Measure target metric at 90% of max IOPS:

```
double high_IOPS = 90% * max_IOPS;

[EditRollup] "all=all" [parameters] "total_IOPS=" + string(high_IOPS);

[Go]  "stepname=\"high_target at 90% of max\", measure = service_time_seconds, timeout_seconds = 600,
accuracy_plus_minus = " + string(accuracy);

// Retrieve "high_target":

set_csvfile(summary_filename);

string result = last_result();  if ("success" != result)
         { s = "Failed to obtain measurement running at 90% of max IOPS.\n";
           print(s); log(masterlogfile(),s); exit(); }

double high_target_ms = double(csvfile_cell_value(2,"Overall Average Service Time (ms)"));

double high_target = high_target_ms / 1000.0;

drop_csvfile(summary_filename);
```

`Adaptive_PID.ivyscript` example

- Run PID loop for service times evenly spaced through operating range:

```
double multiplier, target_value;
string stepname;

for multiplier = { .1, .2, .3, .4, .5, .6, .7, .8, .9 }
{
        target_value = low_target + multiplier * (high_target - low_target);

        stepname = to_string_with_decimal_places(100.0*multiplier,0) + "% of operating range";

        [go] "stepname = \"" + stepname + "\""
                    + ", focus_rollup = all"
                    + ", measure = service_time_seconds"
                    + ", accuracy_plus_minus = " + string(accuracy)
                    + ", measure_seconds = 120"
                    + ", timeout_seconds = " + string( 60 * 25 )
                    + ", dfc = PID"
                    + ", target_value = " + string(target_value)
                    + ", low_IOPS = "      + string(low_IOPS)
                    + ", low_target = "    + string(low_target)
                    + ", high_IOPS = "     + string(high_IOPS)
                    + ", high_target = "   + string(high_target);
}
```

Monitoring PID loop behaviour

- Look in the (main) test output folder for `<test name>.PID.csv`.
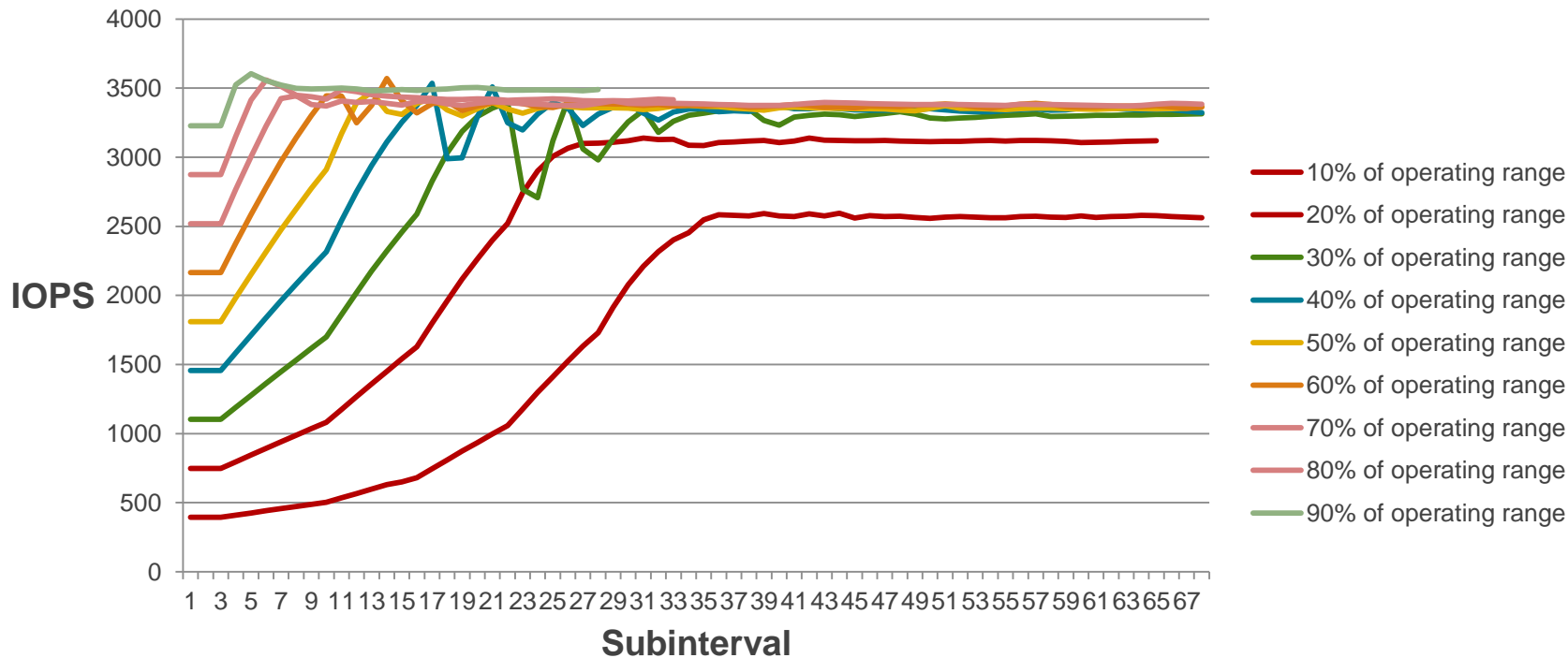
How long will it take?

- It depends very much on the stability of the workload.

- Note that for these 15K HDDs, the time gets much longer near the "knee" of the curve. This is at max ripple & accuracy both 1% with 45 minute timeout.

-
```
********* ivy run complete.  Total run time 2:41:00 for test name "adaptive_PID_2"
********* step0000 duration 0:01:11 "IOPS = max"
********* step0001 duration 0:01:56 "low_target at 1% of max"
********* step0002 duration 0:01:11 "high_target at 90% of max"
********* step0003 duration 0:05:16 "10% of operating range"
********* step0004 duration 0:05:11 "20% of operating range"
********* step0005 duration 0:24:26 "30% of operating range"
********* step0006 duration 0:45:17 "40% of operating range"
********* step0007 duration 0:29:47 "50% of operating range"
********* step0008 duration 0:22:46 "60% of operating range"
********* step0009 duration 0:18:26 "70% of operating range"
********* step0010 duration 0:03:01 "80% of operating range"
********* step0011 duration 0:02:26 "90% of operating range"
ivy engine API shutdown_subthreads()
```

ivyscript has user-defined functions

- We may decide to write a "library" function that does the four steps

  1. `measure = IOPS, IOPS = max`

  2. Measure low IOPS / low target

  3. Measure high IOPS / high target

  4. `dfc = PID, target_value =` t `, low_IOPS =` x `,`
     `low_target =` y `, high_IOPS =` a `, high_target =` b

How it works

What are P, I, and D used for in a PID loop?

- P

  – Used to respond to a perturbation or to follow a moving target.

    – Turn steering wheel a bit right for now to drift back to center of lane.

- I

  – Used to make the long term average measurement reach a stable target.

- D

  – Used to damp instability by limiting the "slew rate" or rate at which we allow the measured value to change towards the target value.

Use of P, I, and D in ivy

- P

  – We expect "noise" in the measurement at a fixed IOPS value, we don't have a moving target, and past history should not affect future measurements.

  – P is set to zero.

- I

  – Our focus in ivy is on setting "I" to make the average measurement value lock onto the target value promptly, but stably.

- D

  – Write Pending can have a significant time lag, so we should classify as "advanced" the topic of using WP as the PID control metric because we'll probably need to use D.

Cumulative error gain

- You want the cumulative error over "sufficiently many" subintervals to drive IOPS.

- If you make the gain too low, the system will be too sluggish to respond.

- If you make the gain too high, IOPS will chase "noise" in individual results from subinterval to subinterval.

The ballpark method

- We define the "operating range" for IOPS to be from 1% to 90% of max IOPS.

- We measure the PID control metric at 1% of max IOPS and at 90% of max IOPS.

- We define the "operating range" for the PID control metric to be from the measurement value at 1% of max IOPS to the measurement at 90% of max.

- We use a straight line between the "low" and "high" measurement points as a very rough estimate to set our initial gain & initial IOPS.

Auto-ranging concept

- Depending on which PID control metric is selected, the numeric range of the target value may vary.

  – For `PG_busy_percent`, the `target_value` used might be 0.8 (80%).

  – For `service_time_seconds` on FMD / SSD, the `target_value` might be be about a thousand times smaller at 0.001 (1 ms).

- Depending on the IOPS scalability of the platform being tested, the IOPS numeric range may vary.

  – A single small 7200 RPM HDD Parity Group might have max IOPS = 500.

  – A large subsystem with FMD / SSD might have a max IOPS in the millions.

`dfc = pid` uses the "cumulative error" gain

- The ivy PID loop formula is **IOPS = gain x cumulative error**.

- Thus the gain needs to be appropriate for both the numeric size of the possible error signal, as well as the IOPS scalability of the platform under test.

- ivy uses an approximation method to pick a rough value for the gain, which will then automatically be adjusted as the PID loop runs.

Example with `measure = service_time_seconds`

Max IOPS

Max IOPS 3958

high_target

AMS2100 15K RAID-1

high_IOPS

low_target

low_IOPS

Service Time, ms

IOPS
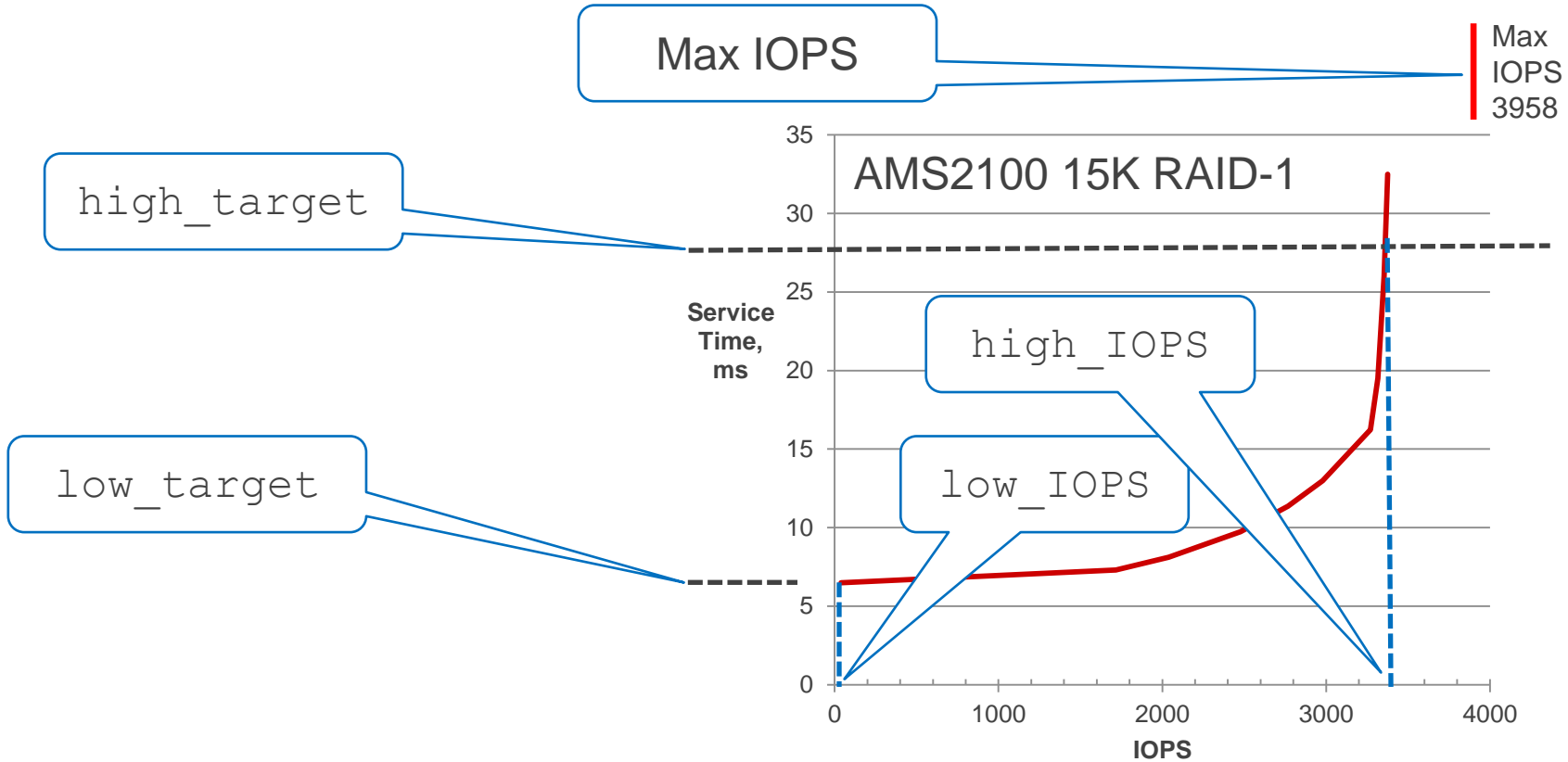
Key concept is "initial error"

The "initial error" is the difference between the target value of the PID control metric, and the baseline value.

The initial error sign is negative.

In this example the initial error of service_time_seconds is -0.006.

Max
IOPS
3958

AMS2100 15K RAID-1

Service
Time,
ms

IOPS
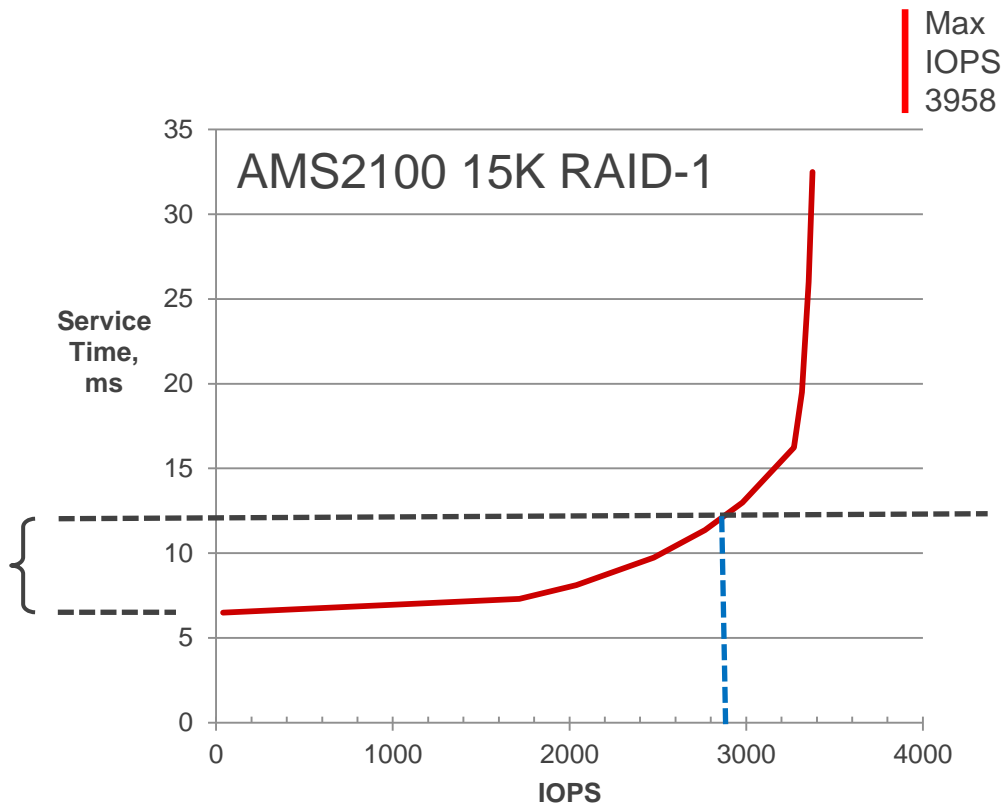
Assume straight line initial error to zero

- Assume error goes to zero in a straight line over "ballpark seconds".

- The average height of a bar, the average error, is ½ of the initial error.

- The cumulative error over the "ballpark seconds" time duration is

½ x (initial error) x (number of subintervals)

= ½ x (initial error) x (ballpark seconds / subinterval duration in seconds)

Initial error

1   2   3   4   5   6   7   8   9   10   11   12

Ballpark seconds

"ballpark seconds" used to set gain sensitivity

- Early experiments with ivy showed that a good tradeoff between responsiveness and stability was to use "`ballpark_seconds`" = 60.

  - Lower `ballpark_seconds`, faster initial response / higher gain.

  - Higher `ballpark_seconds`, slower initial response, lower gain.

- On the previous chart we calculated the estimated cumulative error over the first "ballpark seconds".

- Next, we calculate a rough estimated IOPS drawing a straight line between the "low" and "high" calibration points.

- Then since **IOPS = I x cumulative error**, we calculate starting gain **I = estimated IOPS / estimated cumulative error**.

Effectiveness

- The rough initial estimate followed by the use of the adaptive gain adjustment ensures a rapid approach to the target, followed fine-tuning to stably lock in on the target.

- It doesn't appear to be worth the time to make more than the two calibration measurements.

Solid measurements for range of sensitivities

"ballpark gain too high" group

"ballpark gain too low" group

Ballpark seconds = 30

Ballpark seconds = 60

Ballpark seconds = 120

Ballpark seconds = 240

Ballpark seconds = 480

Overall IOPS

Same data as previous chart – repeatability

Measurements at 1% of max IOPS and 90% of max IOPS provide "ballpark" or rough estimate of PID loop gain, then adaptive algorithm adjusts as needed.

"S" bend in curve probably due to reduction of service time per I/O at higher queue depths.

Service Time, ms

IOPS

- Ballpark seconds 30
- ballpark seconds 60
- ballpark seconds 120
- ballpark seconds 240
- ballpark seconds 480

At the "knee" of the curve, there is more instability in the system, and we can see some variation between repeats of same measurements. This is due to measurement timing out without reaching desired accuracy.