Hi!
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My 3 topics for today:

Parallelism
Asynchrony
Concurrency
There's plenty of confusion around them. They're different. You employ them - or encounter them - in different situations. And they need different solutions.
These topics have a history of pain.

Threads (and data races)

Locks (and deadlocks)

Condition variables (and spurious wakeups)
We've basically *had* the structured programming revolution.
(You get one goto a month!)

We're not doing so well at achieving the same with data.
(But high scale is proving a good teacher.)

But we're making progress on structuring parallelism, concurrency, and asynchrony.
I'm going to take you through some of these structured approaches.

And, since I've been working on Perl 6 implementations of them, I'll use that for my examples.
Let's start with parallelism.
Most modern CPUs have multiple cores
For years, we increased CPU clock speeds by decreasing feature size, bringing components closer so we could compute things faster.
But then...
But then... physics happened
Speed of light – the fastest we can move information

\[
\frac{3.0 \times 10^8 \text{ m/s}}{3.0 \times 10^9 \text{ Hz}} = 10 \text{ cm}
\]

How far we can move information per cycle

Number of cycles a 3GHz CPU does per second
We're already down to making transistors out of just 10s of atoms.
The solution: do multiple things at the same time
Parallelism is about choosing to do multiple things at once, in hope of reaching a solution in less (wallclock) time.
Parallelism is about choosing to do multiple things at once, in hope of reaching a solution in less (wallclock) time.

Parallelism is not something that results from the problem at hand, but from our choice of solution!
use JSON::Tiny;

sub MAIN($file1, $file2) {
    my $parsed1 = from-json(slurp($file1));
    my $parsed2 = from-json(slurp($file2));
    say $parsed1 eqv $parsed2
        ?? 'Files contain identical JSON'
        !! 'Files contain different JSON';
}

Here's a simple JSON comparison program.
There are **two tasks** with **no dependencies** between them.

```perl
use JSON::Tiny;

sub MAIN($file1, $file2) {
    my $parsed1 = from-json(slurp($file1));
    my $parsed2 = from-json(slurp($file2));
    say $parsed1 eqv $parsed2
        ? 'Files contain identical JSON'
        !! 'Files contain different JSON';
}
```
Let's do them in parallel!
But...
But...

How to pick the best number of tasks to work on at a time?

How to wait correctly and efficiently for completion, and correctly get the results?

How do we correctly handle exceptions in parallel work?
use JSON::Tiny;

sub MAIN($file1, $file2) {
    my $parsing1 = start from-json(slurp($file1));
    my $parsing2 = start from-json(slurp($file2));
    my ($parsed1, $parsed2) = await $parsing1, $parsing2;
    say $parsed1 eqv $parsed2
        ?? 'Files contain identical JSON'
        !! 'Files contain different JSON';
}
Use Promises!

```perl
use JSON::Tiny;

sub MAIN($file1, $file2) {
    my $parsing1 = start from-json(slurp($file1));
    my $parsing2 = start from-json(slurp($file2));
    my ($parsed1, $parsed2) = await $parsing1, $parsing2;
    say $parsed1 eqv $parsed2
        ?? 'Files contain identical JSON'
        !! 'Files contain different JSON';
}
```

Schedule work on the thread pool. It can consider hardware, memory, etc. to choose appropriate number of workers.
use JSON::Tiny;

sub MAIN($file1, $file2) {
    my $parsing1 = start from-json(slurp($file1));
    my $parsing2 = start from-json(slurp($file2));
    my ($parsed1, $parsed2) = await $parsing1, $parsing2;
    say $parsed1 eqv $parsed2 ?? 'Files contain identical JSON'
        !! 'Files contain different JSON';
}

Can await any number of Promises; it waits efficiently (OS kernel aware) and unpacks the results for you
Use Promises!

```perl
use JSON::Tiny;

sub MAIN($file1, $file2) {
  my $parsing1 = start from-json(slurp($file1));
  my $parsing2 = start from-json(slurp($file2));
  my ($parsed1, $parsed2) = await $parsing1, $parsing2;
  say $parsed1 eqv $parsed2
    ?? 'Files contain identical JSON'
    !! 'Files contain different JSON';
}
```

Any exceptions thrown by the started code are captured, and then automatically re-thrown on the awaiting thread.
This is **task parallelism**. We find independent tasks, and work on them in parallel.
Here's our next challenge:
Here's our next challenge: parallelizing a program that parses many data files from weather stations, filters out those in Europe, and then finds the place with the maximum temperature.
We'll build a pipeline of operations (hint: in Perl 6, storing the result of things like map and grep in a Scalar lets you talk about the pipeline without evaluating it for results!)

```perl
sub MAIN($data-dir) {
    my $filenames = dir($data-dir);
    my $data      = $filenames.map(&slurp);
    my $parsed    = $data.map(&parse-climate-data);
    my $european  = $parsed.grep(*.continent eq 'Europe');
    my $max       = $european.max(by => *.average-temp);
    say "$max.place() is the hottest!";
}

# Some utility subs omitted here...
```
With this approach, we don't build up a lot of state in memory. One file at a time is pulled through the pipeline.

```
map &slurp
map &parse-climate-data
grep `.*continent eq 'europe'`
```
Here, we're seeking data parallelism. We have many data items, and want to do the same to each of them - so we partition the data.
We'd like to run the pipeline on a bunch of threads, feeding them data and collecting the results.

```
map &slurp
map &parse-climate-data
grep ".continent eq 'europe'"
```

```
map &slurp
map &parse-climate-data
grep ".continent eq 'europe'"
```
But...

How to distribute the work and collect the results safely?

How to collect exceptions?

What if keeping results ordered relative to input matters?
sub MAIN($data-dir) {  
  my $filenames = dir($data-dir).race(batch => 10);  
  my $data = $filenames.map(&slurp);  
  my $parsed = $data.map(&parse-climate-data);  
  my $european = $parsed.grep(*.continent eq 'Europe');  
  my $max = $european.max(by => *.average-temp);  
  say "$max.place() is the hottest!";  
}

# Some utility subs omitted here...

We use race to switch on parallel processing of the pipeline!

Calling .race() coerces the pipeline into a parallel one. Once we reach the max call, multiple threads will be spawned, processing the pipeline on batches of 10 items at a time.
.race(batch => 32, degree => 4)

Run the pipeline in parallel, work in batches of 32 values at a time, and create 4 parallel workers. Produce results in whatever order they become available.

.hyper(batch => 64, degree => 2)

Run the pipeline in parallel, work in batches of 64 values at a time, and create 2 parallel workers. Make sure the results produced are relative to the order of the inputs.
.race()
Run the pipeline in parallel, work out the best batch size and number of workers for me. Produce results in whatever order they become available.

.hyper()
Run the pipeline in parallel, work out the best batch size and number of workers for me. Make sure the results produced are relative to the order of the inputs.
Next up: asynchrony
All about reacting to things that will happen in the future.

Exactly when they happen is not under our direct control.
Examples

Spawned processes completing

Responses to web requests arriving

Incoming connections to a server

User interaction with a GUI

Signals
In some cases, we can start an operation that will complete in the future, and **block** until it does.

But sometimes this doesn't meet our needs - or won't scale far enough.
Example: scp all the things

We have a bunch of files we need to securely copy to many servers

We can run the scp program in a loop to upload them one at a time:

```bash
for @uploads -> $file-info {
    run('scp', $file-info.local, $file-info.target);
}
```

But how might we do 4 at a time?
Using Proc::Async

First, let's adapt our code to use Proc::Async instead (built in to Perl 6):

```perl
for @uploads -> $file-info {
    my $proc = Proc::Async.new('scp',
                                $file-info.local, $file-info.target);
    await $proc.start;
}
```

It's await again! We get a Promise back from $proc.start.
Do them all at once!

To get a step closer, we can now push each Promise onto an array, and then await all of them:

```perl
my @working;
for @uploads -> $file-info {
    my $proc = Proc::Async.new('scp',
        $file-info.local, $file-info.target);
    push @working, $proc.start;
}
await @working;
```

Of course, this hammers the network!
Maximum 4 at a time

If @working grows to 4, we wait for any Promise to be kept, and grep on unkept:

```perl
my @working;
for @uploads -> $file-info {
    my $proc = Proc::Async.new('scp',
        $file-info.local, $file-info.target);
    push @working, $proc.start;

    if @working == 4 {
        await Promise.anyof(@working);
        @working .= grep({ !$_ });
    }
}

await @working;
```
Simple asynchronous operations are started, and produce one result. But some asynchronous data sources produce many values over time.
Asynchronous data streams

File change notifications

Incoming requests to a server

Incoming packets of data to a socket

GUI events
Supplies

In Perl 6, an asynchronous stream of values is called a Supply.
Automated test runner

We'll use a file change notification supply to trigger automated running of a test suite.

We want to watch a test directory, and optionally a number of source directories - and should only do one test run at a time.
File changes

The IO::Notification built-in provides a way to watch for changes

The watch-path method returns a Supply, which we can tap:

```perl
my $changes = IO::Notification.watch-path($test-dir);
$changes.tap({
    say "It changed!";
});
```
Supply is the dual of Seq

Earlier, we set up a pipeline of operations for querying climate data. When we asked for the hottest place, `max` pulled values through the pipeline to work it out.

A `Supply` is also a pipeline, but values are instead pushed through it as they are produced at their (asynchronous) source.
Familiar methods, but async

This means we can use things like map and grep to project and filter data that arrives asynchronously. For example, we can filter by file extension:

```perl
my $changes = IO::Notification.watch-path($src-dir);
my $code = $changes.grep(*.path ~~ /<.pm .p6> $/);
$code.tap({
    say "A source file changed!";
});
```
Nice, but...
Nice, but...

Most people don't solve all of their list-related problems using `map`, `grep`, and other higher order friends.

Some problems are more easily expressed using `for` loops, `if` statements, etc.

But a `for` loop is a blocking, synchronous thing. What about asynchronous data?
Perl 6 has an asynchronous looping construct called *whenever*. The body runs whenever a value arrives:

```perl
whenever IO::Notification.watch-path($test-dir) {
    maybe-run-tests('Tests changed');
}
```

Being a loop, you can even use `LAST` to decide how to handle end of sequence!
A whenever can live in a supply block (which can emit values) or a react block (works like entering an event loop):

```perl
my $code = supply {
    whenever IO::Notification.watch-path($src-dir) {
        emit .path if .path ~~ /<.pm .p6> $/;
    }
}
react {
    whenever $code -> $path {
        say "Code file $path changed!";
    }
}
```
Back to our test runner

On changes to the specified test and source directories, maybe run the tests:

```perl
sub MAIN($test-dir, *@source-dirs) {
  react {
    whenever IO::Notification.watch-path($test-dir) {
      maybe-run-tests('Tests changed');
    }
    for @source-dirs -> $dir {
      whenever IO::Notification.watch-path($dir) {
        maybe-run-tests('Source changed');
      }
    }
    ...
  }
}
```
Deciding whether to run

The notifications may arrive on different threads - but only one thread may be in a supply/react at once - so this is safe:

```perl
sub maybe-run-tests($reason) {
    state $running-tests = False;
    unless $running-tests {
        say "Running tests ($reason)";
        $running-tests = True;
        whenever run-tests() {
            print "\n\n";
            $running-tests = False;
        }
    }
}
```
Actually doing the running

It's our old friend, Proc::Async again. We output STDOUT indented and discard STDERR. We return a Promise; whenever can work fine against those too.

```
sub run-tests() {
    my $runner = Proc::Async.new('prove ...');
    whenever $runner.stdout -> $output {
        print $output.indent(2);
    }
    whenever $runner.stderr { } # Discard
    return $runner.start;
}
```
Perl 6 keeps asynchrony explicit. It provides structured language support, to avoid a tangle of callbacks and guide programmers towards thread safety.
Finally: concurrency
Concurrency is about competition to access and mutate some shared resource.
Passengers checking in for a flight at the same time must not be able to choose the same seat!
class Flight {
    has %!seats;

    submethod BUILD(@seat-labels) {
        %!seats{@seat-labels} = False xx *;
    }

    method choose-seat($seat, $passenger-name) {
        die "No such seat" unless %!seats{$seat}:exists;
        die "Seat taken!" if %!seats{$seat};
        %!seats{$seat} = $passenger-name;
    }
}

A simple seat allocator
But...

The code contains a data race!

```
method choose-seat($seat, $passenger-name) {
    die "No such seat" unless %!seats{$seat}:exists;
    die "Seat taken!" if %!seats{$seat};
    %!seats{$seat} = $passenger-name;
}
```

If two threads are in this method at the same time with the same $seat, they may both see the seat is not taken, and then place their passenger into it!
Solution: a monitor

A monitor is a class where only one thread may be running a method on a particular instance at a time.

So, the second passenger wanting to select a seat would have to wait until the first has finished selecting theirs.

How do we refactor our code?
use OO::Monitors;

monitor Flight {
    has %!seats;

    submethod BUILD(:@seat-labels) {
        %!seats{@seat-labels} = False xx *
    }

    method choose-seat($seat, $passenger-name) {
        die "No such seat" unless %!seats{$seat}:exists;
        die "Seat taken!" if %!seats{$seat};
        %!seats{$seat} = $passenger-name;
    }
}

It's easy!
use OO::Monitors;

monitor Flight {
  has %!seats;

  submethod BUILD(:@seat-labels) {
    %!seats{@seat-labels} = False xx *;
  }

  method choose-seat($seat, $passenger-name) {
    die "No such seat" unless %!seats{$seat}:exists;
    die "Seat taken!" if %!seats{$seat};
    %!seats{$seat} = $passenger-name;
  }
}
But...
But...

Suppose we use a monitor in an asynchronous web application. In the case of contention, one of the processing threads will block synchronously waiting for the other thread to leave the monitor.

Can we do better?
Use an actor instead!

```perl
use OO::Actors;

actor Flight {
    has %!seats;

    submethod BUILD(:@seat-labels) {
        %!seats{@seat-labels} = False xx *;
    }

    method choose-seat($seat, $passenger-name) {
        die "No such seat" unless %!seats{$seat}:exists;
        die "Seat taken!" if %!seats{$seat};
        %!seats{$seat} = $passenger-name;
    }
}
```
What an actor does

An actor puts incoming method calls into a processing queue

Method calls on an actor return a Promise, which the caller awaits:

```javascript
await $flight.choose-seat($seat, $passenger-name);
```

The processing thread is free to deal with other requests in the meantime!
Both actors and monitors factor the concurrency control out of your code, letting you get on with the interesting logic.
In closing...
It's time to embrace structured approaches to parallel, asynchronous, and concurrent programming.
And it's time for our languages to support us in this - especially in providing syntactic relief for asynchronous flow control, which can make a huge difference.
Thank you!

Any questions?