Continuous Regression Testing for Safer and Faster Refactoring

PEJMAN GHORBANZADE

Continuous Regression Testing for Safer and Faster Refactoring

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Aurora Innovation

Engineers spend 17 hours per week maintaining software.

*Stripe 2019 Developer Coefficient Report

Maintaining Software

- Reading
- Refactoring
- Upgrading
- Migrating
- Debugging
- Adding tests
- Writing documentation
- Resolving technical debt

“The only constant in life is change.” - Heraclitus

Types of Change

- Fixing a defect
- Enabling code reuse
- Adjusting to new expectations
- Improving a function implementation
- Upgrading a third-party dependency
- Renaming a function or variable
- Changing system configuration
- Updating build system toolchain

“Software engineering is programming integrated over time.” - *Titus Winters*

It takes 23 days for software engineers to gain confidence that a code change works as expected.

*Tricentis 2021 Report: How The World's Top Organizations Test

Agenda

- **What is continuous regression testing**
- How does regression testing work in practice
- How to build a regression testing system
- Going beyond finding behavioral regressions
- How to use regression testing effectively
- Establishing a culture of safety at scale

About Aurora

Delivering the benefits of self-driving technology, safely, quickly, and broadly.

`aurora.tech/careers`

About Me

- Staff Software Engineer at **Aurora Innovation**
- Building tooling to improve developer experience
- Accelerating the development of web applications
- 8 years of professional experience
- Maintaining mission-critical software systems
- Ex VMware Carbon Black, Canon Medical Informatics
- Former founder of a developer tools startup

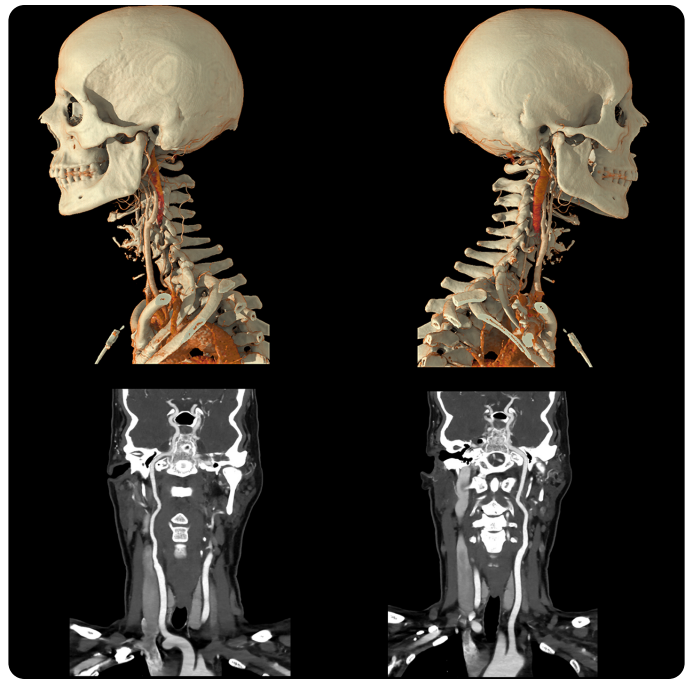
Pejman Ghorbanzade

pejman.dev

What we do matters

Low-dose Ultra Helical CT Angiogram of the Carotids and Circle of Willis for stroke work-up.

Clear visualization of contrast enhanced vessels and surrounding soft tissue enables fast and confident rule-out of occlusion.



Courtesy of Canon Medical Group

Digital Imaging and Communications in Medicine

Group	Element	Tag name
0008	0020	Study date
0008	002A	Acquisition DateTime
0010	0010	Patient’s name
0020	0013	Instance Number
0020	0020	Patient orientation

Courtesy of Canon Medical Group

What could go wrong?

Incorrect interpolation and misrepresenting image positions could result in inaccurate measurements, causing patient harm.

Courtesy of Canon Medical Group

Everything could go wrong

"The inherent complexity of the real world and the continuous change of requirements result in large and complex software systems that are costly and difficult to maintain."

"In a sufficiently long time horizon, all possible behaviors of your system will occur." - *Hyrum's law (modified)*

Testing as risk mitigation

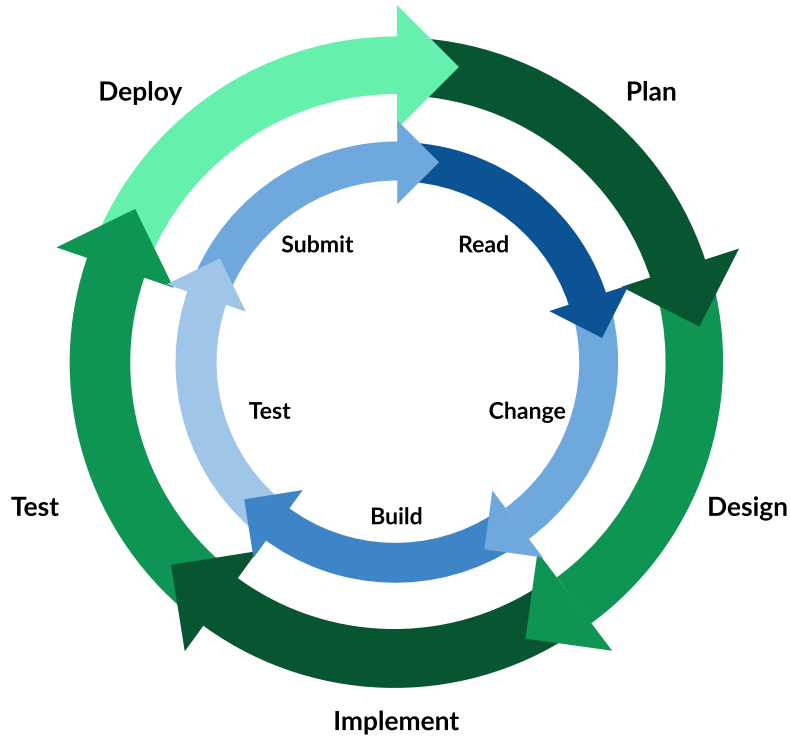
If every code change can break our software, how could we stay productive and safely introduce frequent changes?

Implement high-level tests and continuously run them at scale to cover real-world system behaviors with reasonable degree of confidence.

Developer inner and outer loops

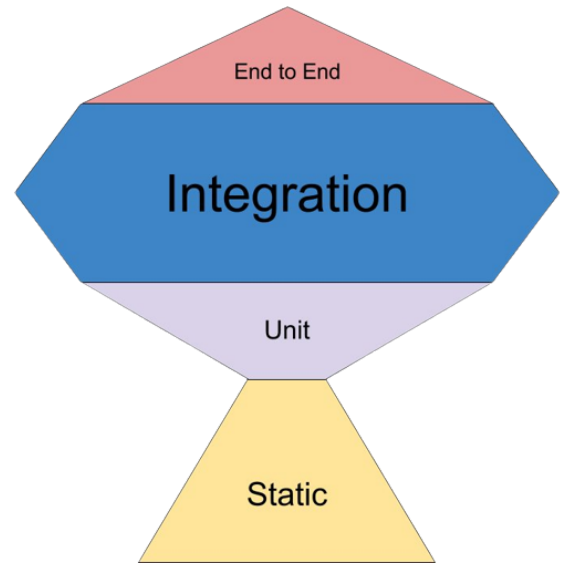
Fast feedback cycles boost development confidence and productivity.

Moving high-level tests out of the developer loop results in slow and inefficient application life-cycles.



The myth of the testing pyramid

Concerns	Benefits
Difficult costly to setup and run	Expressive easy to read and modify
Expensive need system deployment	Scalable can run many test cases
Slow take long to execute	Comprehensive cover component interactions
Brittle flaky and easy to break	Reassuring provide more confidence



"Write tests. Not too many. Mostly integration." - Guillermo Rauch

Continuous regression testing

Continuously verifying that the software works as well as before, during the development stage.

Testing for Correctness

- Requires describing the expected behavior for each test input.
- Mismatches against the expected values indicate failure.
- Tests are difficult to maintain, scale, and automate.

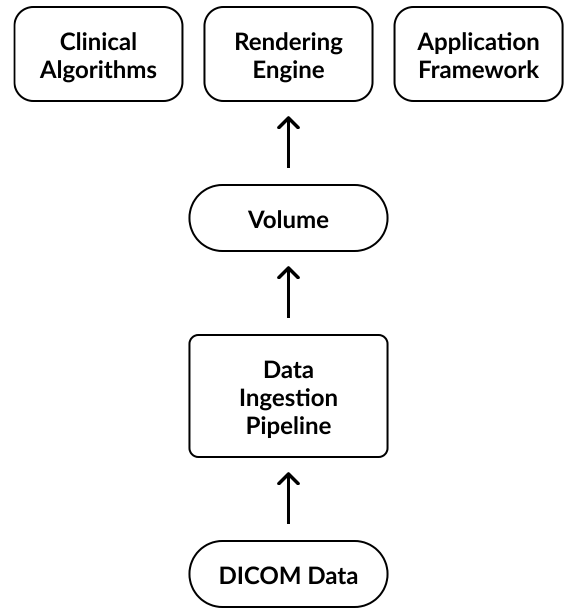
Testing for Regression

- Treats a released version of software as baseline.
- Mismatches against the baseline require justification.
- Tests are expressive and decoupled from the test input.

Higher-level tests in practice

Safely rewriting a critical data ingestion pipeline

500,000 + lines of code	12,000 + real-world datasets
10,000 + attributes to verify	16,000 + gigabytes of input data



In-Memory Comparison

- Test is difficult to setup
- Test system is inefficient to run
- Test system is not reuseable

50,000 +
LoC test framework

16 +
hours to run test

```
for (auto test_case: test_suite) {
 auto new_output = new_system(test_case);
 auto old_output = old_system(test_case);
 auto report = compare(new_output, old_output);
 report.store(test_case);
}
generate_summary_report();
```

Snapshot Testing

Debugging

System is treated as a black box. Output may miss important data.

Reliability

Output may include nondeterministic data.

Data Management

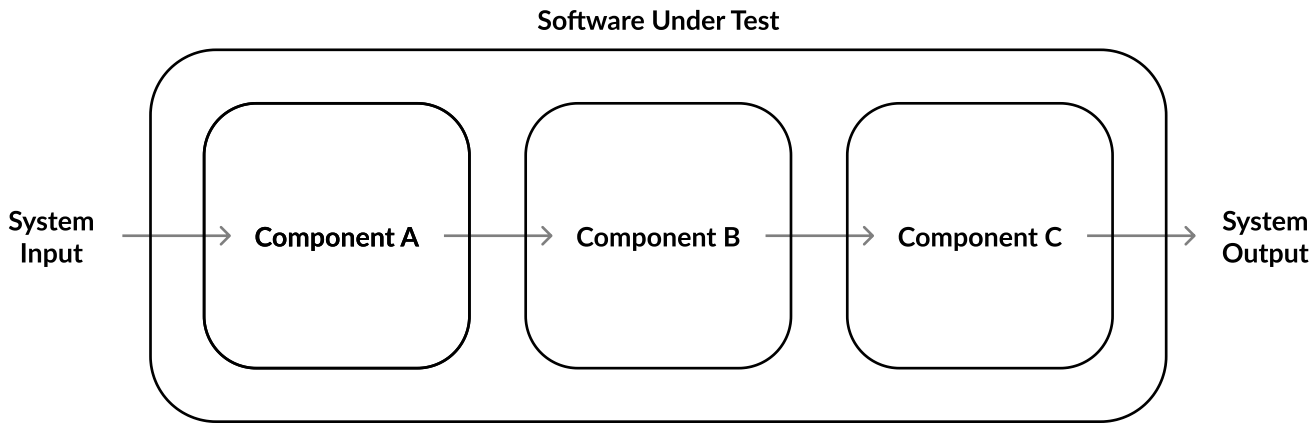
Output is stored in version control along with source code.

Reporting

Differences are difficult to inspect, understand, and manage.

```
for (auto test_case: test_suite) {
 auto new_output = new_system(test_case);
 store_snapshot(test_case, new_output);
 auto old_output = load_snapshot(test_case);
 auto report = compare(new_output, old_output);
 report.store(test_case);
}
generate_summary_report();
```

Problem: Debugging



Good tests point to the root cause when they fail.

Problem: Reliability

Snapshot tests

- are prone to capturing non-deterministic data.
- are prone to capturing unimportant data.
- may leave out changes not captured in the output.
- fail to compare captured data in their original type.

Good tests pass and fail only when they are supposed to.

```
         The Alameda ALM 408-207-1126
               777 The Alameda
             San Jose, CA 95126
  CANTALOUPE                          $3.99 F
    *Sale*            $3.32          -$0.67
    Prime Extra 10.00%               -$0.33
           Subtotal:                  $3.99
           Total Savings:            -$1.00
           Net Sales:                 $2.99
               Total:                 $2.99
               Sold Items:               1

****************************************

      901 61797 09/15/2023 05:46 PM
```

Problem: Data Management

```
$ git status
On branch feature/cppcon
Your branch is up to date with 'origin/feature/cppcon'.

Changes not staged for commit:
  (use "git add <file>..." to update what will be committed)
  (use "git restore <file>..." to discard changes in working directory)
    modified:   SuperMarketTest.TenPercentDiscount.approved.txt
    modified:   SuperMarketTest.BuyOneGetOneDiscount.approved.txt
```

Good test systems enable auditing how software evolves.

Problem: Reporting

```
$ git diff
index 3de4787..5ad5e04 100644
--- a/SuperMarketTest.TenPercentDiscount.approved.txt
+++ b/SuperMarketTest.TenPercentDiscount.approved.txt
@@ -1,5 +1,5 @@
 apples                                4.97
   1.99 * 2.500
-Total:                                4.47
+Total:                                4.97
```

Good test systems report insights as output, not raw test results .

Design Principles

Developer Friendly

Designed for everyday use by developers. Should enable creating tests that are cheap to write, fast to run, and easy to modify.

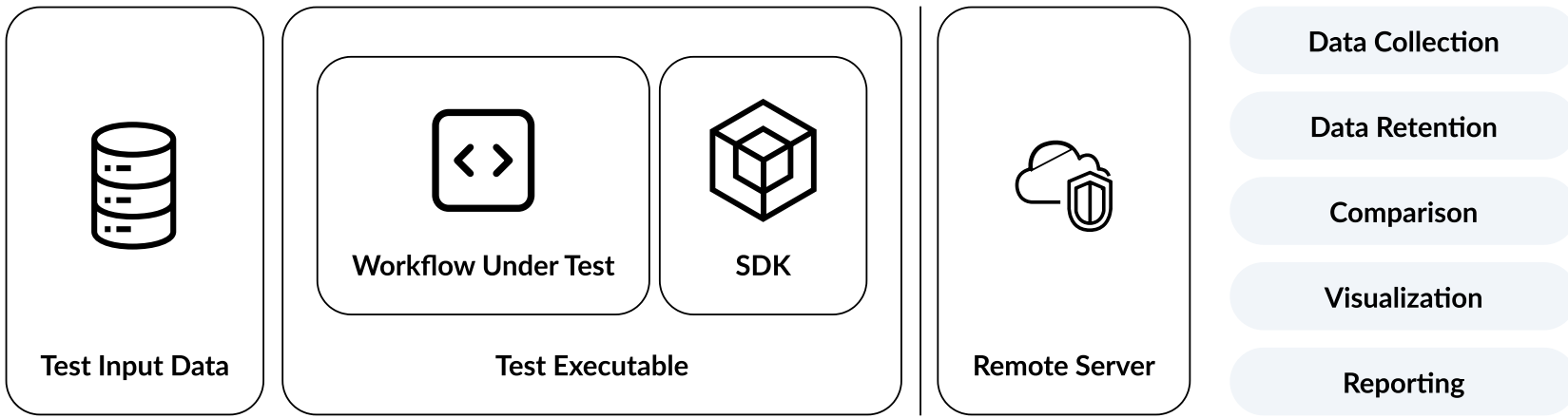
Flexible

Designed for capturing values of variables and runtime of functions. Should handle data points with primitive or user-defined data types.

Scalable

Designed for testing mission-critical software. Should handle capturing data from large number of test cases and report test results as actionable insights.

Rethinking snapshot testing



About Touca

touca.io

Find the unintended side-effects of your day-to-day code changes

Trusted By:

Canon

Backed By:

techstars_

Agenda

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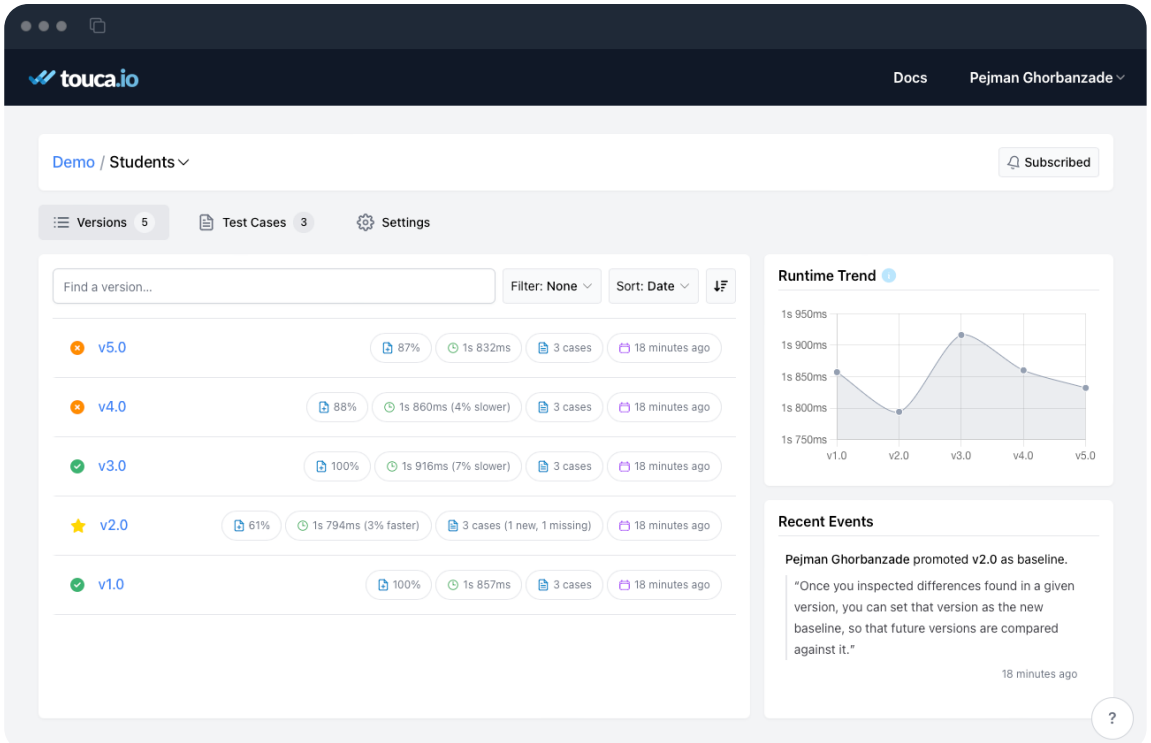
Touca Server

Remotely compare the output of your software against a previous baseline version.

- Free and Open Source
- Developer Friendly
- Language Agnostic
- Battle Tested



Self-hosting

github.com / **trytouca**

```
$ brew install touca
$ touca server install
```

Apache 2.0 License

Test Framework

```cpp
#include "catch2/catch.hpp"
#include "students.hpp"

TEST_CASE("find_students") {
  SECTION("alice") {
    auto student = find_student("alice");
    CHECK(student.name == "Alice Anderson");
    CHECK(student.dob == Date(2006, 3, 1));
    CHECK(student.gpa == 3.9);
  }
  SECTION("bob") {
    auto student = find_student("bob");
    CHECK(student.name == "Bob Brown");
    CHECK(student.dob == Date(1996, 6, 31));
    CHECK(student.gpa == 3.8);
  }
  SECTION("charlie") {
    auto student = find_student("charlie");
    CHECK(student.name == "Charlie Clark");
    CHECK(student.dob == Date(2003, 9, 19));
    CHECK(student.gpa == 3.3);
  }
}
```

```cpp
#include "touca/touca.hpp"
#include "students.hpp"

int main(int argc, char* argv[]) {
  touca::workflow("find_students", [](const std::string& username) {
    const auto& student = find_student(username);
    touca::check("name", student.name);
    touca::check("birth_date", student.dob);
    touca::check("gpa", student.gpa);
  });
  return touca::run(argc, argv);
}
```

- Parses command-line arguments
- Retrieves test cases
- Submits captured data
- Reports test progress
- Handles any errors

Writing tests

Test your complex software workflows for any number of inputs by capturing values of variables and runtime of functions.

```cpp
#include "students.hpp"
#include "touca/touca.hpp"

int main(int argc, char* argv[]) {
  touca::workflow("find_student", [](const std::string& username) {
    const auto& student = find_student(username);
    touca::assume("username", student.username);
    touca::check("fullname", student.fullname);
    touca::check("birth_date", student.dob);
    touca::check("gpa", student.gpa);
    touca::check("pass", student.gpa < 3.9);
    touca::add_metric("external_source", 1500);
  });
  return touca::run(argc, argv);
}
```

Running tests

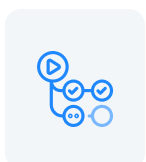
Run your tests for each code change or pull request, as part of CI or on a dedicated test machine, to get fast feedback during the development stage.

```
$ brew install touca
$ touca login
$ touca test
```

```
$ touca test

Touca Test Runner

Suite: students/v2

 1. PASS   alice      (209 ms)
 2. DIFF   bob        (223 ms)
 3. PASS   charlie    (217 ms)

Tests:      2 perfect, 1 different, 3 total
Time:       1.45 s

✨  Ran all test suites.
```

Automating tests

Integrate your tests with the CI/CD pipeline to automate their execution and receive feedback when you need it.

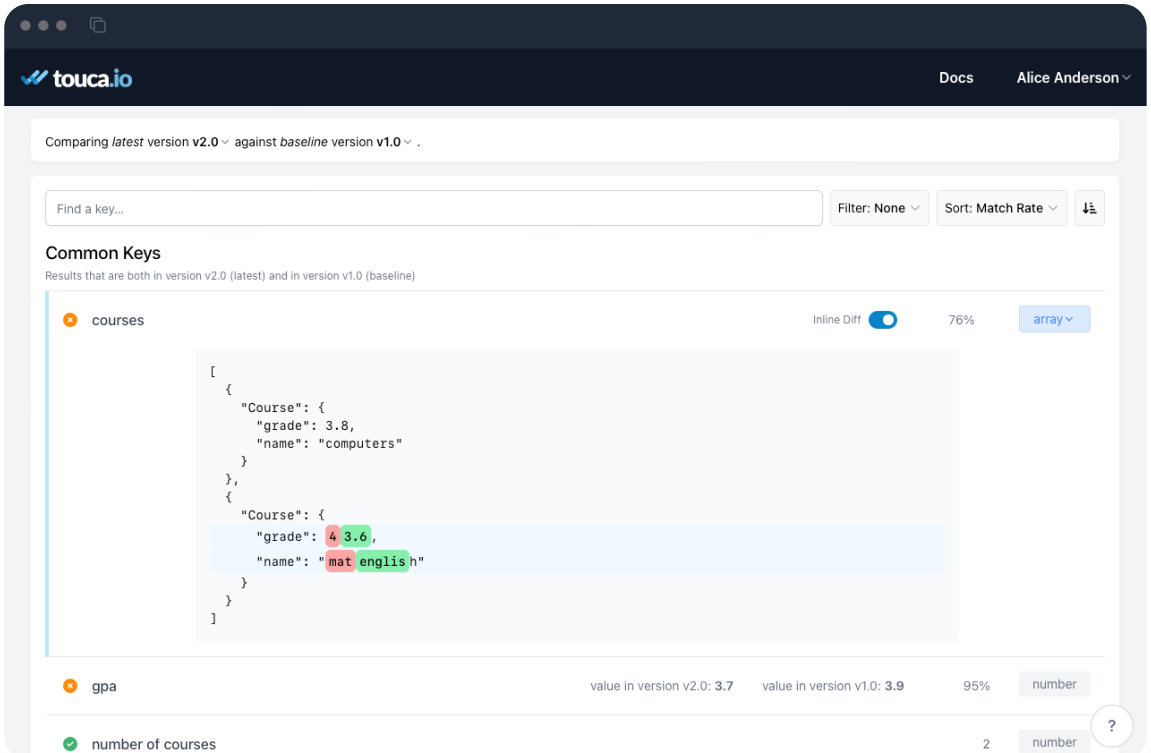



```yaml
- name: build cpp app
  run: ./build.sh
- uses: trytouca/actions-run-tests@v1
  env:
    TOUCA_API_KEY: ${{ secrets.TOUCA_API_KEY }}
    TOUCA_API_URL: https://api.touca.io/@/my_org/my_cpp_app
    TOUCA_TEST_VERSION: ${{ steps.params.outputs.version }}
  with:
    executable: ./local/dist/bin/my_cpp_app
```

Visualizing differences

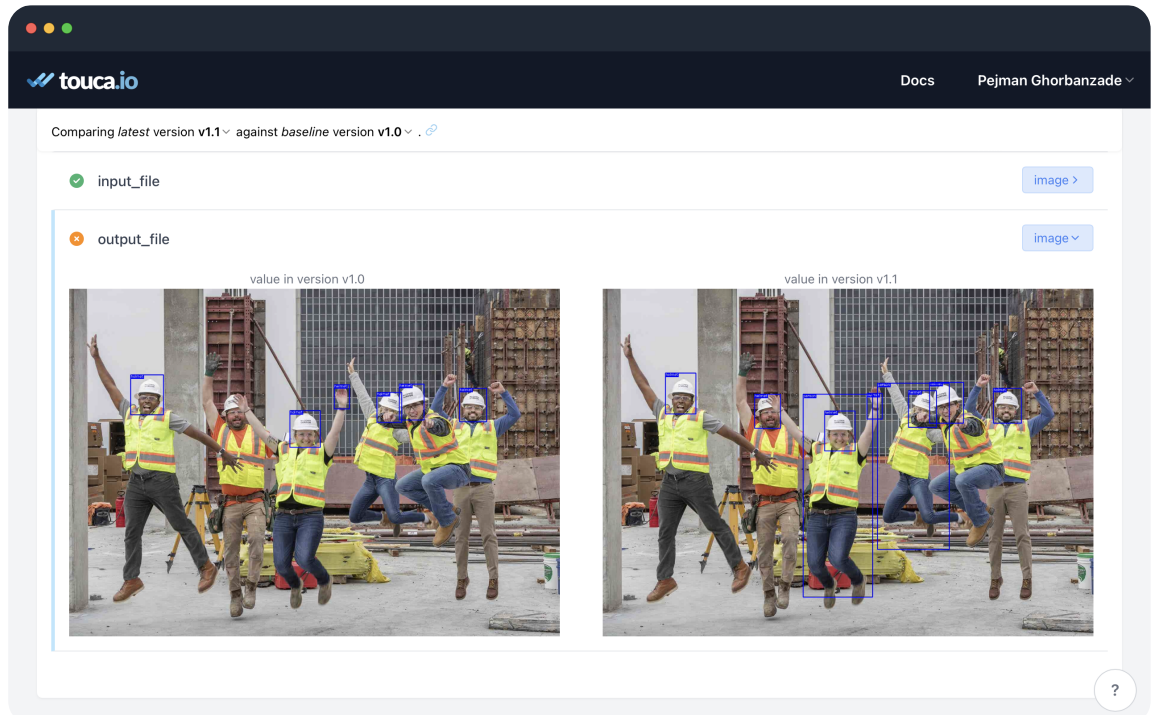
Automatically compare new test results and visualizing inspect potential differences against your baseline.

- Automatic and on-demand comparison
- Overall insights and summary reports
- Custom comparison rules



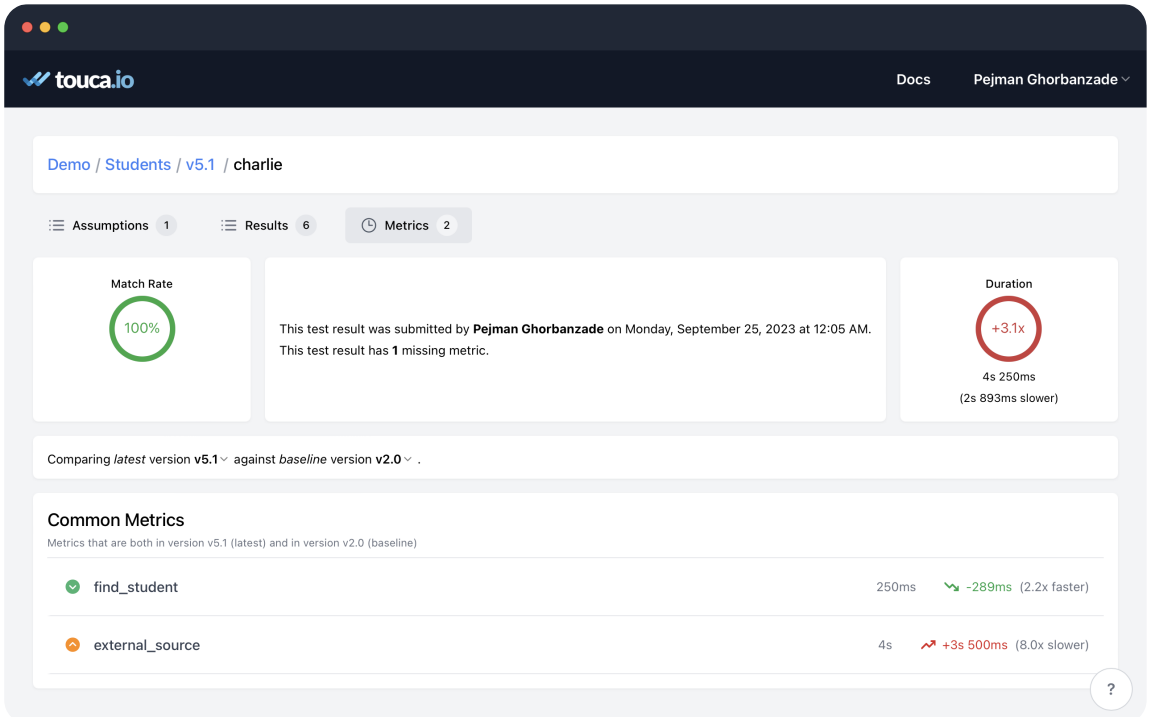
Comparing images and videos

Share test results with team members and visualize differences of any kind.



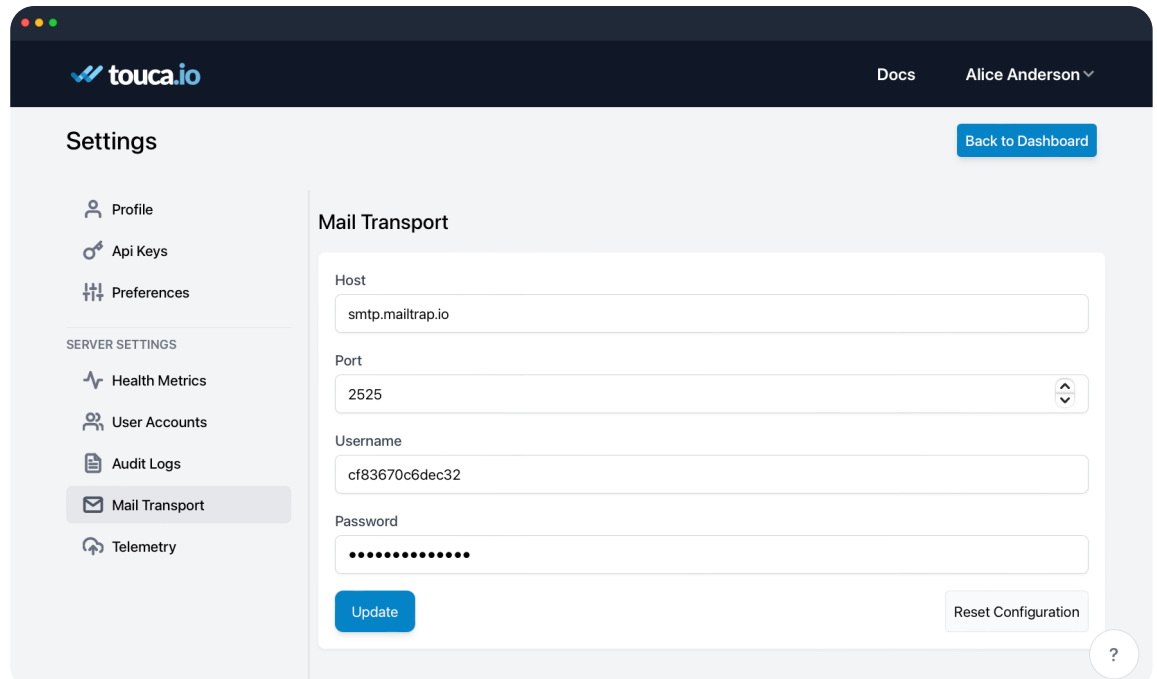
Finding performance regressions

Gain insights and analytics about how your software is evolving over time.



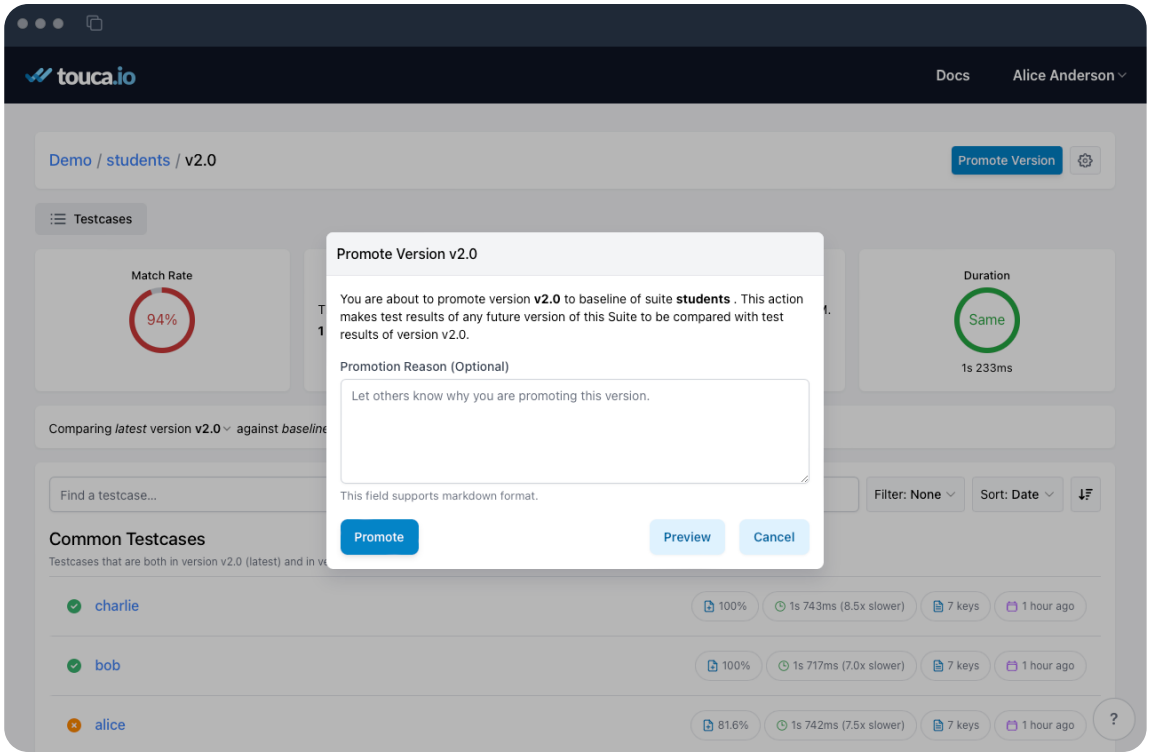
Reporting Results

Subscribe to any suite to get notified about new regressions.



Baseline Management

Collaborate with your team members in investigating regressions and managing baseline versions.



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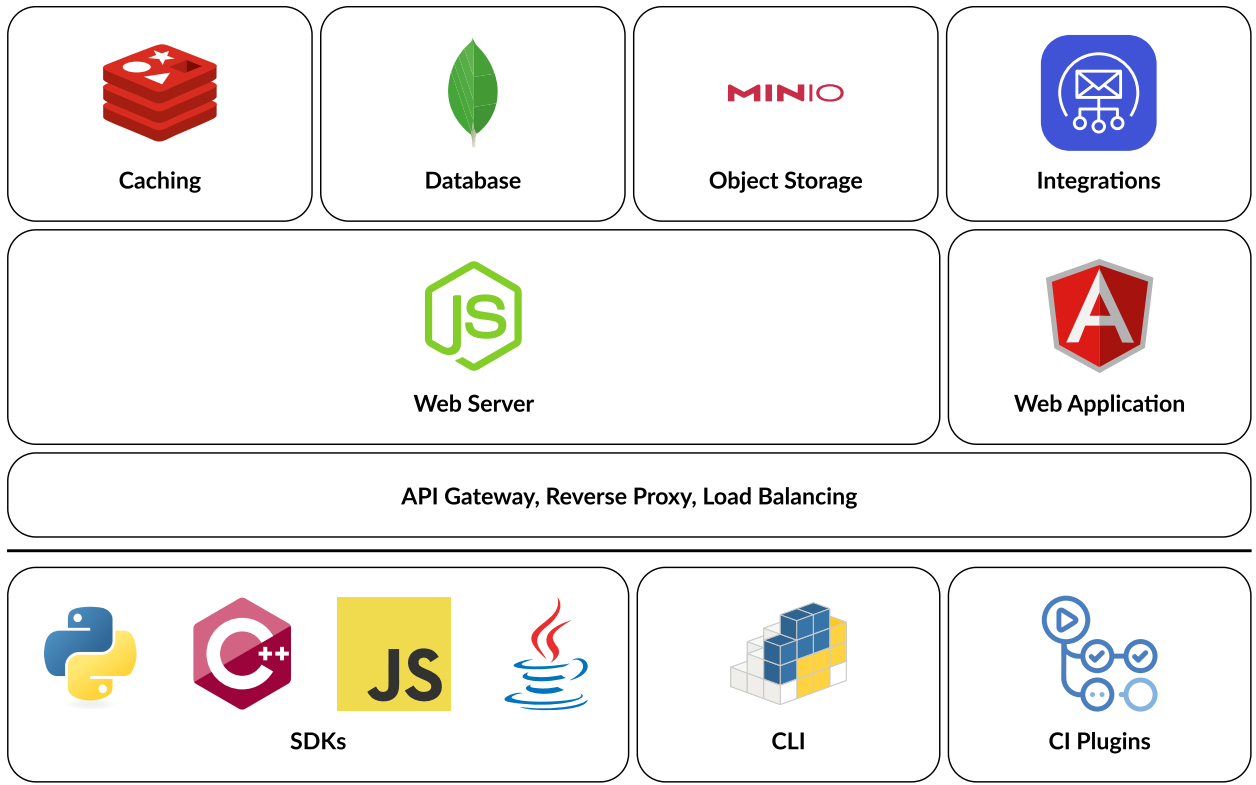
System Architecture



C++ SDK

GCC	Clang	MSVC
9.4.0	11.0.0	1900

C++11 through C++23

CMake	Conan	Bazel
3.14	v1	v6.3.2

```
$ ./build.sh
info       building cpp library using cmake
-- Fetching third-party dependency: flatbuffers
-- Fetching third-party dependency: fmt
-- Fetching third-party dependency: ghcfilesystem
-- Fetching third-party dependency: httplib
-- Fetching third-party dependency: rapidjson
-- Fetching third-party dependency: mpark_variant
-- Fetching third-party dependency: cxxopts
-- Configuring done (32.6s)
-- Generating done (0.0s)
-- Install configuration: "Release"
-- Installing: ./local/dist/lib/libtouca.a
-- Installing: ./local/dist/licenses/LICENSE
$
```

🔗 touca.io/docs/sdk/installing

Data Capturing API

```
touca::workflow("students", [](const std::string& username) {
  const auto& student = find_student(username);
  touca::check("name", student.name);
  touca::check("birth_date", student.dob);
  touca::check("gpa", student.gpa);
});
```

```
struct Date {
  unsigned short year;
  unsigned short month;
  unsigned short day;
};
```

```
template <typename Char, typename Value>
void check(Char&& key, const Value& value) {
  touca::detail::check(std::forward<Char>(key),
                       serializer<Value>().serialize(value));
}
```

Capturing behavior data

```
touca::log("timestamp", student.created_at);
```

```
touca::assume("username", student.username);
```

```
for (const auto& course : student.courses) {
  touca::add_array_element("courses", course);
  touca::add_hit_count("number of courses");
}
```

```
void Client::check(const std::string& key, const data_point& value) {
  if (has_last_testcase()) {
    _testcases.at(get_last_testcase())->check(key, value);
  }
}
```

Capturing performance data

```
touca::start_timer("find_student");
const auto& student = find_student(username);
touca::stop_timer("find_student");
```

```
Student find_student(const std::string& username) {
  touca::scoped_timer timer("find_student");
  // ...
}
```

```
with touca.scoped_timer("find_student"):
    student = find_student(username)
```

```
touca::add_metric("external_source", 1500);
```

Partial Template Specialization

```
template <typename T, typename = void>
struct serializer {
  data_point serialize(const T& value) {
    static_assert(std::is_same<data_point, T>::value,
                  "did not find any specialization of "
                  "serializer for the given type");
    return static_cast<T>(value);
  }
};
```

Specializing Standard Types

```
template <typename T>
using is_number_signed =
    conjunction<negation<std::is_same<T, bool>>,
                std::is_integral<T>,
                std::is_signed<T>>;
```

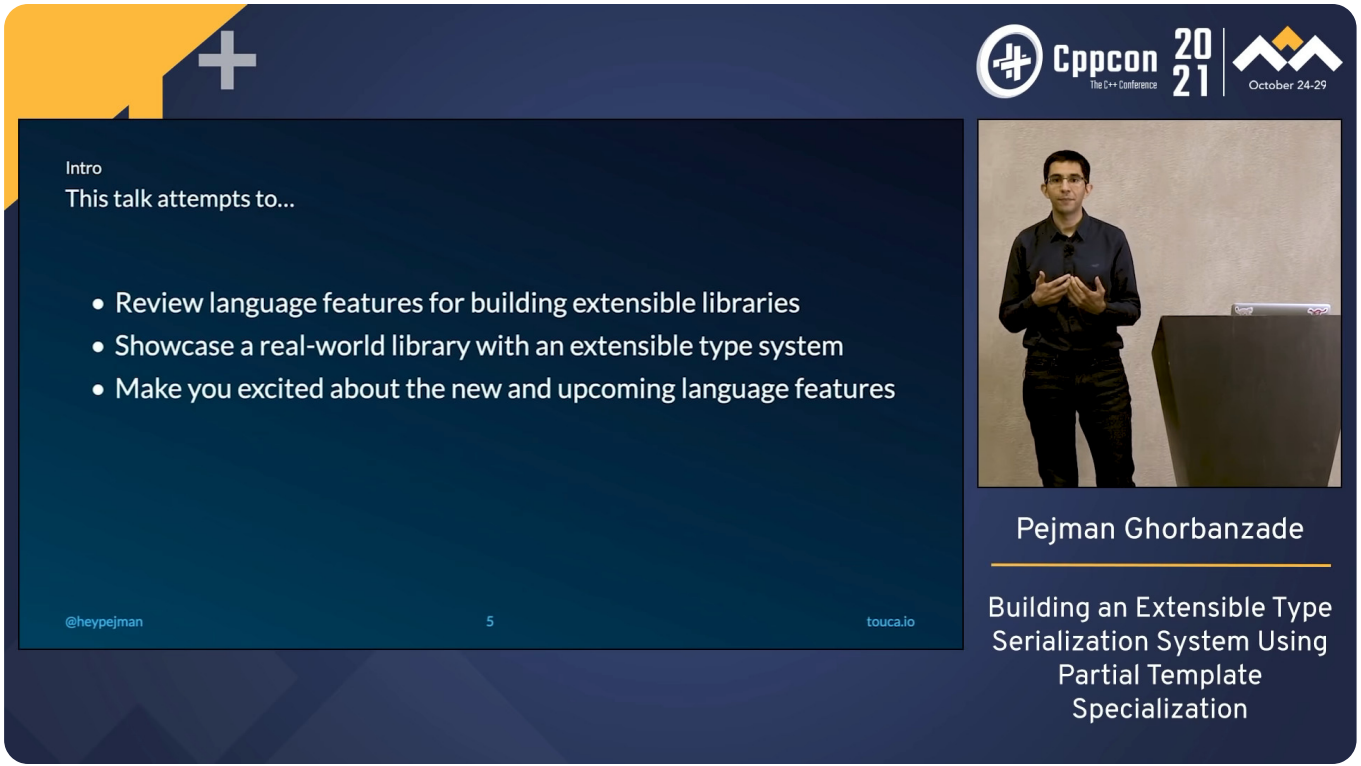
```
template <typename T>
struct serializer<
    T, enable_if_t<is_number_signed<T>::value>> {
  data_point serialize(const T& value) {
    return data_point::number_signed(value);
  }
};
```

```
enum class internal_type : std::uint8_t {
  null,
  object,
  array,
  string,
  boolean,
  number_signed,
  number_unsigned,
  number_float,
  number_double,
  unknown
};
```

Specializing User-Defined Types

```
template <>
struct serializer<Date> {
  data_point serialize(const Date& date) {
    return object("Date")
        .add("year", date.year)
        .add("month", date.month)
        .add("day", date.day);
  }
};
```

Deeper Dive



🔗 `pejman.dev/talks/cppcon21`

Low-Level API

```
touca::workflow("students", [](const std::string& username) {
  const auto& student = find_student(username);
  touca::check("name", student.name);
  touca::check("birth_date", student.dob);
  touca::check("gpa", student.gpa);
});
```

```
Post::Status ClientImpl::post() const {
  /** ... */
  const auto& buf = Testcase::serialize(testcases);
  std::string content((const char*)buf.data(), buf.size());
  const auto& response = transport->binary(content);
  /** ... */
}
```

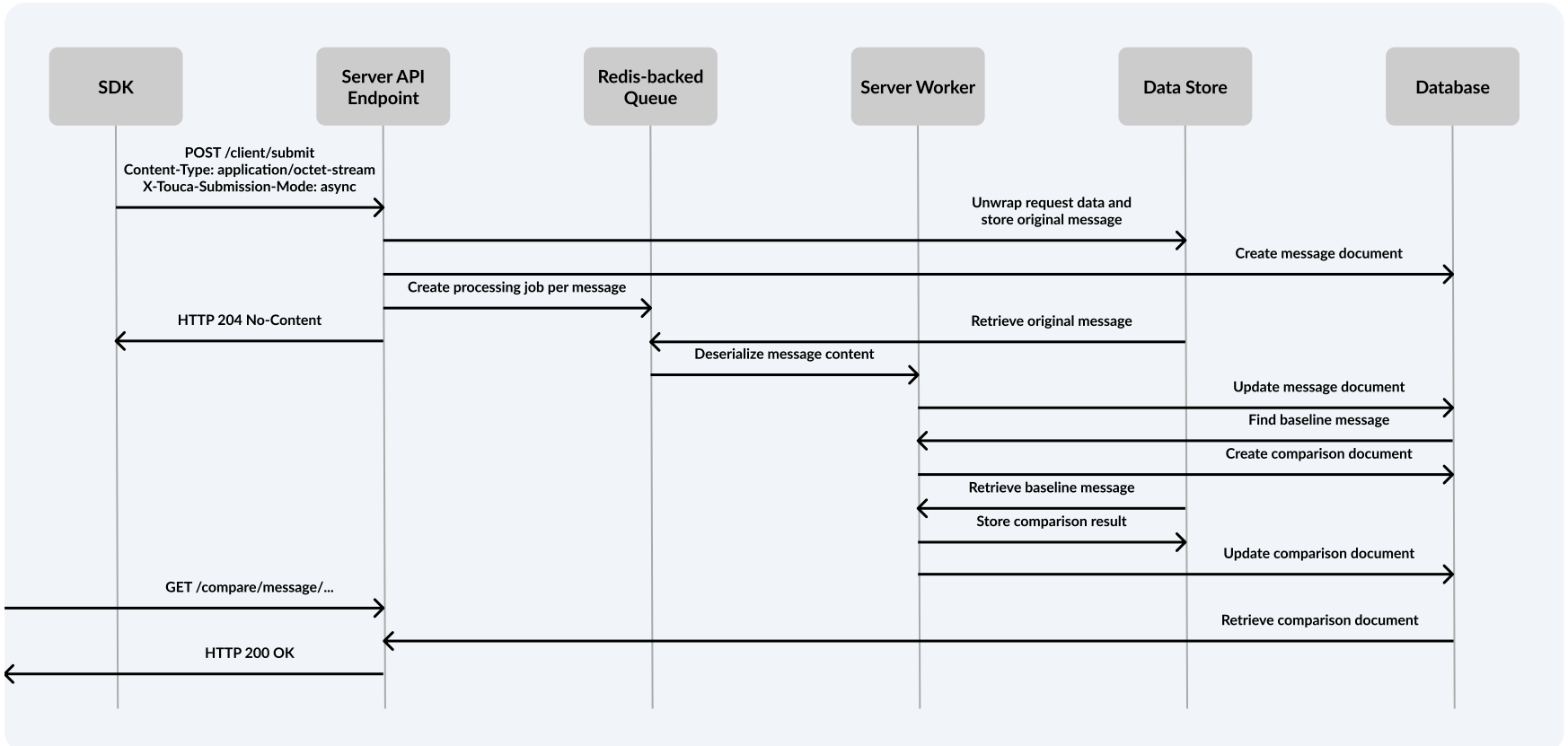
```
int main() {
  touca::configure();
  for (const auto& username : {"alice", "bob", "charlie"}) {
    touca::declare_testcase(username);
    const auto& student = find_student(username);
    touca::check("name", student.name);
    touca::check("birth_date", student.dob);
    touca::check("gpa", student.gpa);

    touca::post();
    touca::save_binary("touca_" + username + ".bin");
    touca::save_json("touca_" + username + ".json");
    touca::forget_testcase(username);
  }
  touca::seal();
}
```

FlatBuffers Schema

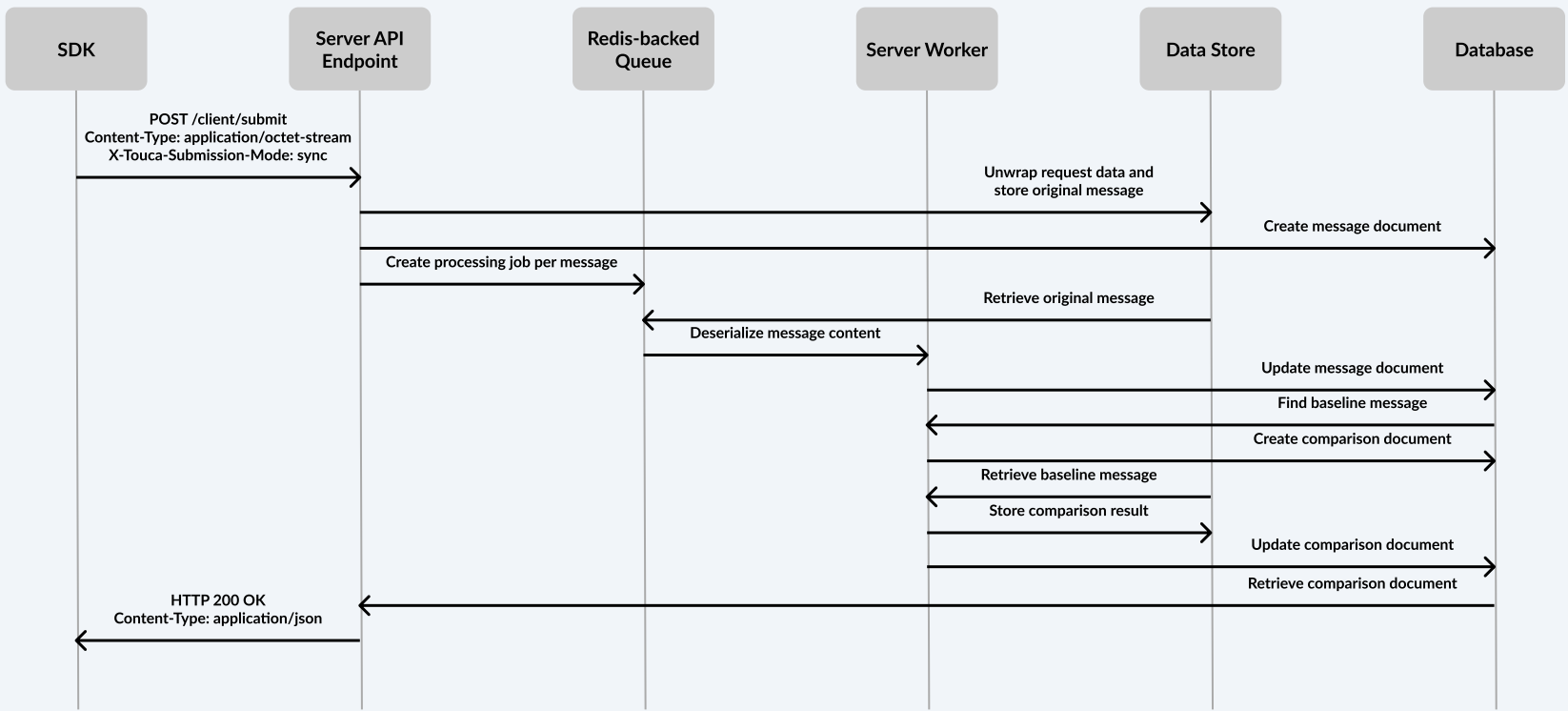
```
union Type {
  Bool,
  Int,
  /** ... */
  String,
  Object,
  Array
}
table TypeWrapper {
  value:Type;
}
table Result {
  key:string;
  value:TypeWrapper;
}
```

```
table Results {
  entries:[Result];
}
table Message {
  metadata:Metadata;
  results:Results;
  metrics:Metrics;
}
table MessageBuffer {
  buf:[uint8] (nested_flatbuffer: "Message");
}
table Messages {
  messages:[MessageBuffer];
}
root_type Messages;
```

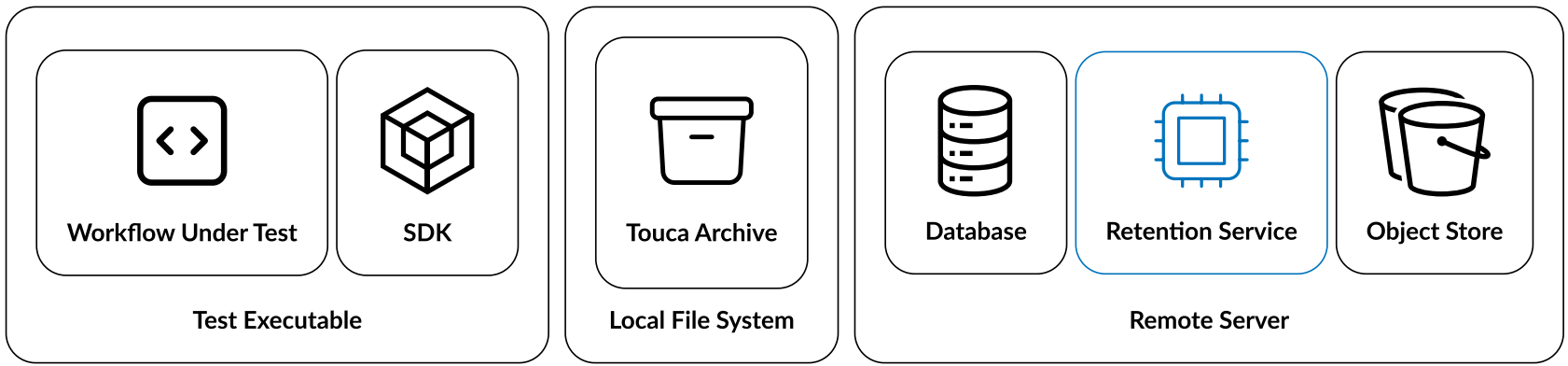
Data ingestion w/ async processing



Data ingestion w/ on-demand processing



Data Retention



- Local Filesystem Backup
- Configurable Retention Duration

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Custom comparison rules

Language Agnostic

Real-Time Feedback

```
touca::check("gpa", student.gpa, touca::decimal_rule::min_absolute(3));
```

3.8

Actual value
Version v5.1

3.9

Previous value
Version v2.0

Value passes minimum threshold of **3**.

Tracking performance benchmarks

```cpp
#include <benchmark/benchmark.h>

static void BM_String(benchmark::State& state) {
  for (auto _ : state)
    std::string empty_string;
}

BENCHMARK(BM_String);
BENCHMARK_MAIN();
```

```
$ touca plugin add plugins://google_benchmark
$ touca google_benchmark output.json
```

```json
{
  "context": {
    "date": "2023/09/25-18:40:25",
    "num_cpus": 40,
    "mhz_per_cpu": 2801,
    "cpu_scaling_enabled": false,
    "build_type": "debug"
  },
  "benchmarks": [
    {
      "name": "BM_String",
      "iterations": 94877,
      "real_time": 29275,
      "cpu_time": 29836,
      "bytes_per_second": 134066,
      "items_per_second": 33516
    }
  ]
}
```

Profiling build times

```
$ bazel build :sample_app --generate_json_trace_profile \
   --profile sample_app.profile.gz --noslim_json_profile
$ bazel analyze-profile sample_app.profile.gz
=== PHASE SUMMARY INFORMATION ===

Total launch phase time                                    0.014 s    0.42%
Total init phase time                                      0.048 s    1.46%
Total target pattern evaluation phase time                 0.006 s    0.19%
Total interleaved loading-and-analysis phase time          0.153 s    4.64%
Total preparation phase time                               0.001 s    0.05%
Total execution phase time                                 3.084 s   93.19%
Total finish phase time                                    0.001 s    0.03%
---------------------------------------------------------------------------
Total run time                                             3.309 s  100.00%
```

```
$ touca plugin add plugins://bazel
$ touca bazel sample_app.profile.gz
```

Profiling the size of binaries

```
$ ./bloaty bloaty -d compileunits
    FILE SIZE        VM SIZE
 --------------  --------------
  57.5%  17.4Mi    68%  4.60Mi    [175 Others]
  17.2%  5.08Mi   4.3%   295Ki    third_party/protobuf/src/google/protobuf/descriptor.cc
   7.3%  2.14Mi   2.6%   179Ki    third_party/protobuf/src/google/protobuf/descriptor.pb.cc
   4.6%  1.36Mi   1.1%  78.4Ki    third_party/protobuf/src/google/protobuf/text_format.cc
   3.7%  1.10Mi   4.5%   311Ki    third_party/capstone/arch/ARM/ARMDisassembler.c
   1.3%   399Ki  15.9%  1.07Mi    third_party/capstone/arch/M68K/M68KDisassembler.c
   3.2%   980Ki   1.1%  75.3Ki    third_party/protobuf/src/google/protobuf/generated_message_reflection.cc
   3.2%   965Ki   0.6%  40.7Ki    third_party/protobuf/src/google/protobuf/descriptor_database.cc
   1.8%   549Ki   1.7%   114Ki    src/bloaty.cc
 100.0%  29.5Mi 100.0%  6.69Mi    TOTAL
```

```
$ touca plugin add plugins://bloaty
$ touca bloaty ./bloaty
```

Tracking exported symbols of a shared library

```
$ nm -gU ./my.dylib | grep touca
000000000006ad64 T __ZNK5touca8Testcase11flatbuffersEv
000000000006a514 T __ZNK5touca8Testcase4jsonEv
000000000006a358 T __ZNK5touca8Testcase7metricsEv
0000000000069508 T __ZNK5touca8Testcase8Metadata4jsonEv
0000000000069370 T __ZNK5touca8Testcase8Metadata8describeEv
00000000000691b0 T __ZNK5touca8Testcase8Overview4jsonEv
0000000000069310 T __ZNK5touca8Testcase8metadataEv
000000000006b9ec T __ZNK5touca8Testcase8overviewEv
```

```
$ touca plugin add plugins://cpp_symbols
$ touca cpp_symbols ./my.dylib --filter touca
```

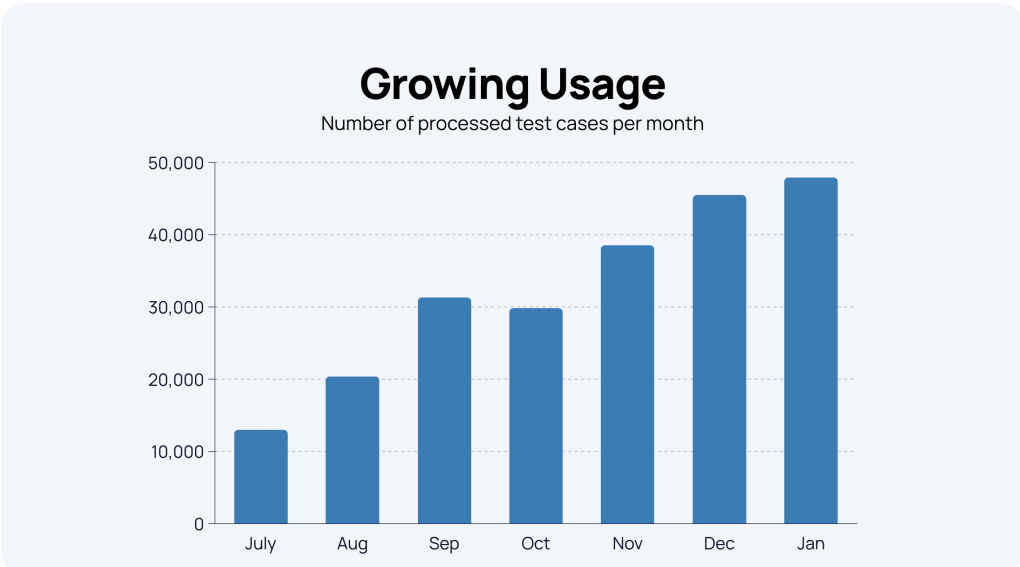
Agenda

- What is continuous regression testing
- How does regression testing work in practice
- How to build a regression testing system
- Going beyond finding behavioral regressions
- **How to use regression testing effectively**
- Establishing a culture of safety at scale

A roller coaster story

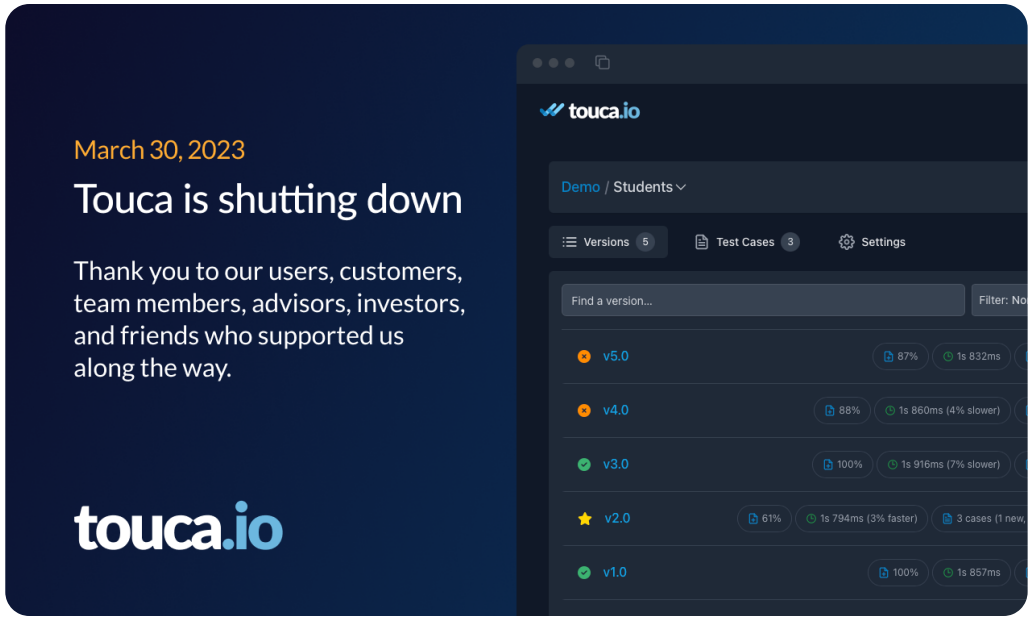
"Touca gives us the confidence to develop new features faster and with fewer problems."

- 10+ paying customers
- 100+ workflows continuously tested
- 1000+ unexpected regressions found



A humbling journey

> "Success is stumbling from failure to failure with no loss of enthusiasm."
>
> - Winston Churchill



touca.io/blog/touca-shutting-down

Broken windows theory

"If a window in a building is broken and is left unrepaired, all the rest of the windows will soon be broken. [...] Window-breaking does not necessarily occur on a large scale because some areas are inhabited by determined window-breakers, rather, one unrepaired broken window is a signal that no one cares, and so breaking more windows costs nothing."

The Atlantic, 1982

AI-generated

No tool can address software quality issues more effectively than fostering a culture of continuous improvement.

Improving software quality

Culture

Teams need to foster ownership and accountability for software quality. reward continuous improvements and actively share about technical debt.

Commitment

Teams need to commit to continued investment in maintaining software quality and continuously measure their RoI by tracking developer productivity.

Education

Engineers need to understand their product to know what to test, and learn how to write tests that are fast to run, cheap to maintain, and reliable to use.

Improving team culture

- Maintaining software quality is a collective effort.
- Shift-left testing reduces development cost and improves efficiency.
- Effective communication about software quality helps improve it.

- Reward and promote continuous improvements.
- Continuously measure developer experience and productivity.

Proving business value

Continuously:

- Measure developer experience and productivity.
- Monitor changes to developer feedback cycles.
- Track the effectiveness of existing testing practices.
- Extract real-time insights about software development life-cycle.

Learning what to test

- Good tests verify a system expectation that is prone to change.
- Good tests are the ones that fail from time to time.
- Good tests make efficient use of the resources they need.

Scope

Confidence

By Etienne Jong

Learning how to test

Expressive

Good tests are easy to read and effective way of learning business logic. Apply the same code hygiene to your tests as your production code.

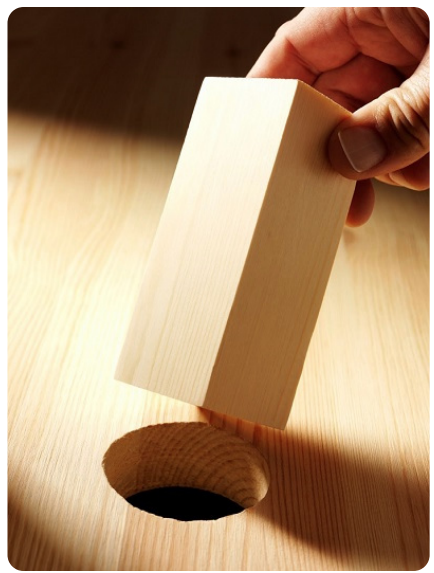
Scalable

Good tests are reusable. Optimize for low per-input execution cost. Prefer writing test code with loose assumptions about individual test inputs.

Extensible

Good tests are easy to change. Optimize for low maintenance cost. Single use-case test frameworks have the same cost as production code.

Measure test coverage in terms of verified business requirements.



Learning when to run each test

Reliability

Fast Feedback

- Optimize for return on investment.
- Avoid reusing paradigms of a specific test stage in others.
- Leverage selective test execution for shorter feedback cycle.
- Use periodic test execution for more confidence.

Learning how to read code

- Understand the business.
- Learn code context and history.
- Ask questions and share concerns.
- Take ownership and accountability.

Learning how to change code

- Understand the system
- Study the call-sites
- Resolve unexpected use cases
- Measure the impact
- Mitigate surprises
- Favor incremental rollout
- Communicate your thought process
- Share changes to expectations

“Take many more much smaller steps.” — GeePaw Hill

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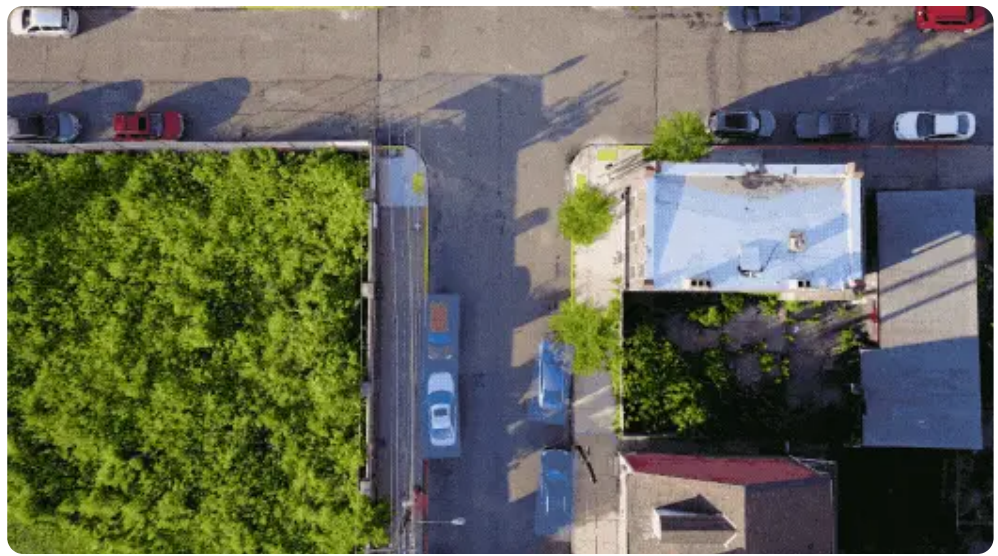
- **Establishing a culture of safety at scale**

What we do matters

- Unit and Integration Tests
- Simulation Tests
- Perception Scenarios
- Hardware-in-The-Loop Tests
- On-vehicle Tests



Simulation Tests

60,000 CPUs utilized
each hour

6 million Simulation runs
per day

6 billion Equivalent miles
driven to date

Virtual world-building

Simulating how sensors perceive objective events in the world, helps curate realistic rare-event scenario data that are difficult, dangerous, or expensive to acquire in the real world.

Machine Learning

1. Data Selection
2. Data Labeling
3. Synthetic Data Generation
4. Model Training
5. Model Evaluation

Safety Case Framework

Goal: Aurora's self-driving vehicles are acceptably safe to operate on public roads.

Proficient

The self-driving vehicle is acceptably safe duration nominal operation.

Fail-Safe

The self-driving vehicle is acceptably safe in presence of faults and failures.

Continuously Improving

Safety issues are resolved with appropriate corrective and preventative actions.

Resilient

The self-driving vehicle is acceptably safe in case of misuse and unavoidable events.

Trustworthy

The self-driving enterprise is trustworthy.

Conclusion

- Fast feedback cycles improve developer experience and boost productivity.
- Continuous regression testing facilitates changing software safely and with confidence.
- Shift-left testing reduces development cost and improves efficiency.
- Maintaining software quality requires fostering a culture of continuous improvements.
- Ensuring software safety requires incorporating multiple software testing methods.

Questions

pejman.dev / talks / cppcon23

github.com / trytouca / trytouca

touca.io / docs

Appendix

Data Capturing Internals

```
void touca::detail::check(const std::string& key, const data_point& value) {
  instance.check(key, value);
}
```

```
void Client::check(const std::string& key, const data_point& value) {
  if (has_last_testcase()) {
    _testcases.at(get_last_testcase())->check(key, value);
  }
}
```

```
void Testcase::check(const std::string& key, const data_point& value) {
  _resultsMap.emplace(key, ResultEntry{value, ResultCategory::Check});
  _posted = false;
}
```

Serializing User-Defined Types - Implementation

```
class object final {
 public:
  explicit object(std::string arg_name) : name(std::move(arg_name)), _v() {}

  template <typename T>
  object& add(std::string&& key, T&& value) {
    using type = typename std::remove_cv<typename std::remove_reference<T>::type>::type;
    _v.emplace(std::move(key), serializer<type>().serialize(std::forward<T>(value)));
    return *this;
  }

  /** ... */

 private:
  std::string name;
  std::map<std::string, data_point> _v;
}
```

Serializing Test Cases

```
std::vector<uint8_t> Testcase::serialize(const std::vector<Testcase>& testcases) {
  flatbuffers::FlatBufferBuilder builder;
  std::vector<flatbuffers::Offset<fbs::MessageBuffer>> messageBuffers;
  for (const auto& tc : testcases) {
    const auto& out = tc.flatbuffers();
    messageBuffers.push_back(fbs::CreateMessageBufferDirect(builder, &out));
  }
  const auto& messages = fbs::CreateMessagesDirect(builder, &messageBuffers);
  builder.Finish(messages);
  const auto& ptr = builder.GetBufferPointer();
  return {ptr, ptr + builder.GetSize()};
}
```

Serializing Data Points

```
std::vector<uint8_t> Testcase::flatbuffers() const {
  /**  ... */
  std::vector<flatbuffers::Offset<fbs::Result>> fbsResultEntries;
  for (const auto& result : _resultsMap) {
    const auto& key = result.first.c_str();
    const auto& value = result.second.val.serialize(builder);
    fbsResultEntries.push_back(fbs::CreateResultDirect(builder, key, value));
  }
  /** ... */
}
```

```
flatbuffers::Offset<fbs::TypeWrapper> data_point::serialize(
    flatbuffers::FlatBufferBuilder& builder) const {
      return touca::detail::visit(data_point_serializer_visitor(builder), _value);
    }
)
```