École polytechnique de Louvain

Observing the detailed behaviour of large distributed applications in real time using △QSD

Author: **Francesco Nieri**
Supervisor: **Peter Van Roy**
Readers: **Tom Barbette, Peer Stritzinger, Neil Davies**

Academic year 2024–2025
Master [120] in Computer Science

Abstract

It is difficult to study the detailed behaviour of large distributed systems while they are running. What happens when there is an overload? Modern software development practices successfully fail to adequately consider essential quality requirements or even to consider properly whether a system can actually meet its intended outcomes. Current observability tools do not meet observability requirements when it comes to detecting problems early enough in running systems.

To tackle these problems, PNSol Ltd. developed the ΔQSD paradigm a novel metrics-based and quality-centric paradigm that uses formalised outcome diagrams to explore the performance consequences of design decisions, as a performance blueprint of the system. PNSol Ltd. analyses the behaviour of existing systems using ΔQSD, but the technology only works a posteriori, there is no way yet to analyse a system's behaviour in real time.

To advance the usage of ΔQSD in distributed projects, we developed the ΔQ oscilloscope, a dashboard to observe a running Erlang system in real time. The oscilloscope works by communicating to a stub which is attached to an Erlang system, the "system under test", which sends outcome instances to the oscilloscope.

In order to use the ΔQ Oscilloscope, the first step is to determine the system's outcome diagram. The system's outcome diagram is a directed graph that shows the causal relationships between the system's internal operations (called outcomes) and its overall inputs and outputs. Each outcome corresponds to a system component. It has a start event and stop event, when the component is called and when it returns.

For each outcome of interest, an observation point (probe) is attached to measure the delay of that outcome. As many probes are put into the system as are needed to observe the desired system behaviours. The probes are implemented on top of OpenTelemetry tracing ability. Each probe sends a time series of data to the ΔQ Oscilloscope, which performs statistical computations on all the time series and displays the results in real time.

AI disclaimer

AI was used to help writing the dashboard interface and to help with the Erlang side. The written master thesis was written entirely without the aid of AI.

Contents

Chapter 1

Introduction

1.1 Context

ΔQSD is an industrial-strength approach for large-scale system design that can predict performance and feasibility early on in the design process. Developed over 30 years by a small group of people around Predictable Network Solutions Ltd, the paradigm has been applied in various industrial-scale problems with huge success and large savings in costs. [1] This project will develop a practical tool, the **ΔQ Oscilloscope**, for the Erlang developer community.

The Erlang language and Erlang/OTP platform are widely used to develop distributed applications that must perform reliably under high load. The tool will provide useful information for these applications both for understanding their behaviour, for diagnosing performance issues, and for optimizing performance over their lifetime.

The ΔQ Oscilloscope will perform statistical computations to show real time graphs about the performance of system components. With the oscilloscope prototype we will present in this paper, we are aiming to show that the ΔQSD paradigm is not only a theoretical paradigm, but it can be employed in a tool to diagnose large distribute systems.

Modern software development practices successfully fail to adequately consider essential quality requirements or even to consider properly whether a system can actually meet its intended outcomes, particularly when deployed at scale, the ΔQSD paradigm addresses this problem!

The oscilloscope targets large distributed applications handling many independent tasks where performance and reliability are important.

ΔQSD has important properties which make its application to distributed projects interesting, it supports:

- A compositional approach that considers performance and failure as first-class citizens.
- Stochastic approach to capture uncertainty throughout the design approach.

- Performance and feasibility can be predicted at high system load for partially defined systems

While the paradigm has been successfully applied in **a posteriori** analysis, there is no way yet to analyse a distributed system which is running in real time! This is where the ΔQ oscilloscope comes in.

1.2 Previous work

The ΔQSD paradigm has been formalised across different papers [2] [3] and was brought to the attention of engineers via tutorials [1] and to students at Université Catholique de Louvain [4].

A Jupyter notebook workbench has been made available on GitHub [5], it shows real time ΔQ graphs for typical outcome diagrams but is not adequate to be scaled to real time systems, it is meant as an interactive tool to show how the ΔQSD paradigm can be applied to real life examples.

Observability tools such as Erlang tracing [6] and OpenTelemetry [7] lack the notions of failure as defined in ΔQSD, which allows detecting performance problems early on, we base our program on OpenTelemetry to incorporate already existing notions of causality and observability to augment their capabilities and make them suitable to work with the ΔQSD paradigm.

1.3 Contributions

There are a few contributions that make the master thesis and thus, the oscilloscope, possible:

- A graphical interface to display ΔQ plots for outcomes.
- An Erlang OpenTelemetry wrapper to give OpenTelemetry spans a notion of failure and to communicate with the oscilloscope.
- An implementation of a syntax, derived from the original algebraic syntax to create outcome diagrams.
- The implementation of ΔQSD concepts from theory to practice, allowing outcomes and probes to be displayed and analysed on the oscilloscope.
- An efficient convolution algorithm based on the FFTW3 library.
- A system of triggers to catch rare events when system behaviour fails to meet quality requirements, giving a snapshot of the system, giving the user insights about their system's behaviour.
- Synthetic applications to test the effectiveness of ΔQSD on diagnosing systems and their feasibility.

These contributions can show that the ΔQSD has its practical applications and is not limited to a theoretical view of system design

1.4 Roadmap

The following thesis will give the reader everything that is needed to use the Oscilloscope and exploit it to its full potential.

We divided the thesis in multiple chapters, below is the roadmap of the content:

- The background chapter gives the reader an introduction to the tools we leverage in our program, namely, OpenTelemetry and an extensive background into the theoretical foundations of ΔQSD, which are the basis of the oscilloscope and are fundamental to understand how to correctly use and analyse the output given by the oscilloscope.
- The design chapter delves into how the parts of the system interact together.
- The implementation part is split in two. First, we provide a high level abstraction of how ΔQSD is implemented in the oscilloscope. Secondly, a more low level explanation, which goes into more technical details of the parts that compose the oscilloscope.
- Lastly, we provide synthetic applications which have been tested with the oscilloscope and an evaluation of the performance of the oscilloscope.

We end by providing future possibilities which can be explored, and concepts which we believe ought to be implemented in observabilities tools. In the appendix, we provide a user manual to help users use the oscilloscope, along with Erlang and C++ source code of the oscilloscope and the wrapper.

Chapter 2

Background

This chapter aims to provide firstly a complete background of the concepts key to understanding the ΔQSD, giving a good basis to grasp the concepts of **quality attenuation** (ΔQ) and outcome diagrams (SD).

Secondly, we provide a comprehensive background into the observability solutions that have been explored for the oscilloscope, delving deeper into OpenTelemetry and its macros.

2.1 An overview of ΔQSD

ΔQSD is a metrics-based, quality-centric paradigm that uses formalised outcome diagrams to explore the performance consequences of design decisions. [2]

Key concepts of ΔQSD are **quality attenuation (ΔQ)** and **outcome diagram**

Outcome diagrams capture observational properties of the system. The ΔQSD paradigm derives bounds on performance expressed as probability distribution, encompassing all possible executions of the system.

The following sections are a summary of multiple articles and presentation formalizing the paradigm. [2] [1] [3] [15]

2.1.1 Outcome

Assume a component C which receives a message m_{in} and outputs a message m_{out} after a delay d. Over multiple executions, we will have observed multiple delays which can be represented as a cumulative definition where p percent of delays have delay $\leq d$. [3] Each outcome has a ΔQ.

An outcome O is a specific system behaviour that can be observed to start at some point in time and ***may*** be observed to complete at some later time. [15] Formally, what the system obtains by performing one of its tasks. One task corresponds to one outcome and viceversa. When an outcome is performed, it means that the task of an outcome is performed.

Observables Each outcome has two starting sets of events: the starting sets and the ending sets. Such sets are called the *observables*. Once an event from the starting set occurs, there is no guarantee that a corresponding event in the terminating set will occur within the duration limit (required time to complete). An observable is *done* when it occurs during the time limit.

Outcome instance Given a starting event e_{in} and an end event e_{out}, an *outcome instance* is what the system gains within (e_{in}, e_{out}).

Representation Outcome are represented as circles, with the starting and terminating set of events being represented by boxes.

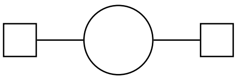


Figure 2.1: The outcome (circle) and the starting set (left) and terminating set (right) of events

2.1.2 Quality attenuation (ΔQ)

ΔQ is a cumulative distribution function that defines both latency and failure probability between a start and end event [1]

In an ideal system, an outcome would deliver a desidered behaviour without error, failure, delay, but this is not the case. The quality of an outcome response "attenuated to the relative ideal" (the cumulative distribution function) is called "quality attenuation" (ΔQ). Since it can depend on many factors (geographical, physical . . .), ΔQ is modeled as a random variable.

As ΔQ captures deviation from ideal behavior, and incorporates delay, which is a continuous random variable, and failures/timeouts, which are discrete variables, it can be described mathematically as an *Improper Random Variable*, where the probability of a delay < 1. Combining latency and failure together makes it easy to examine the tradeoffs between them.

ΔQ(x) will be the probability that an outcome O will occur in time $t \leq x$.

The ***intangible mass*** $1 - \lim_{x \to \infty} \Delta Q(x)$ of a ΔQ will encode the probability of failure/timeout/exception occuring.

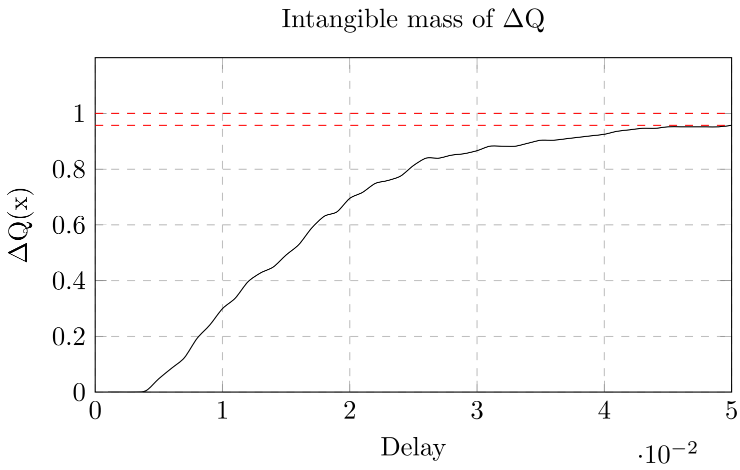


Figure 2.2: Intangible mass (red) of a ΔQ, the observable had a failure rate of about 5%

2.1.3 Failure semantics

Quality attenuation models both delay and failure. In the CDF representation of a ΔQ, there is an f percent probability that the delay is infinite, this is what failure models.

Concretely, it means that an input message m_{in} has no output message m_{out}.

Combining delay and failure in a single quantity is what makes ΔQSD a great choice to explore feasibility in system design.

2.1.4 Partial ordering

A CDF of a ΔQ is *less than* the other if its CDF is everywhere to the left and above the other. Mathematically, it is a partial order.

If two ΔQs intersect, they are not ordered.

2.1.5 Timeliness

Timeliness is defined as a relation between an observed ΔQ_{obs} and a required ΔQ_{req}. Timeliness is delivering results within required time bounds (sufficiently often).

A system *satisfies timeliness* if $\Delta\text{Q}_{obs} \leq \Delta\text{Q}_{req}$.

2.1.6 QTA, required ΔQ

The Quantitative Timeliness Agreement maps objective measurements to the subjective perception of application performance [cite]. It specifies what the base system does and its limits

QTA example : Imagine a system where 25% of the executions should take < 15 ms, 50% < 25 ms and 75% < 35 ms, all queries have a maximum delay of 50ms and 5% of executions can timeout, the QTA can be represented as a step function.

Slack When ΔQ is strictly less than the requirement, we say there is performance *slack*.

Hazard When ΔQ is strictly greater than the requirement, there is performance hazard.

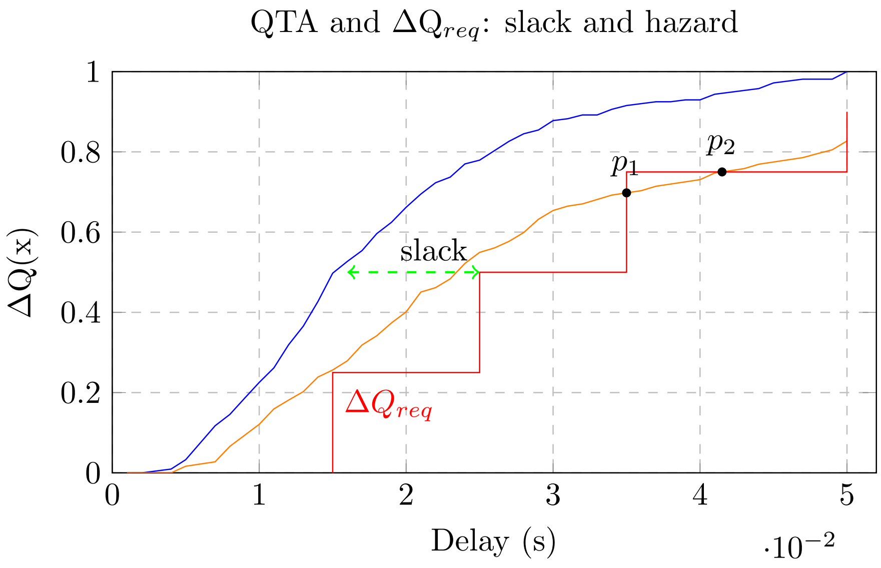


Figure 2.3: The system in blue is showing slack and satisfies the requirement, the system in orange is showing signs that it cannot handle the stress, it is not respecting the ΔQ$_{req}$

.

2.1.7 Outcome diagram

An outcome diagram captures the causal relationships between the outcomes, each outcome diagram can be presented algebraically with an outcome expression. It allows computing the ΔQ for the whole system. The outcome diagram should capture the essential observational properties of a system. There are four different ways to represent the relationships between outcomes.

Sequential composition

If we assume two outcomes O_A, O_B where end event of O_A is the start event of O_B, the ΔQ of O_A and O_B is given by the convolution of the PDFs of O_A and O_B. Where convolution (⊛) between two PDF is :

$$PDF_{AB}(t) = \int_{0}^{t} PDF_A(\delta) \cdot PDF_B(t-\delta)d\delta \tag{2.1}$$

and thus ΔQ$_{AB}$:

$$\Delta Q_{AB} = \Delta Q_A \circledast \Delta Q_B \tag{2.2}$$

First to finish

If we assume two independent outcomes O_A, O_B with the same start event, first-to-finish occurs when at least one end event occurs, it can be calculated as:

$$\begin{aligned}\Delta Q_{FTF(A,B)} &= Pr[d_A > t \wedge d_B > t] \\ &= Pr[d_A > t] \cdot Pr[d_B > t] = (1 - \Delta Q_A) \cdot (1 - \Delta Q_B) \\ \Delta Q_{FTF(A,B)} &= \Delta Q_A + \Delta Q_B - \Delta Q_A \cdot \Delta Q_B\end{aligned} \tag{2.3}$$

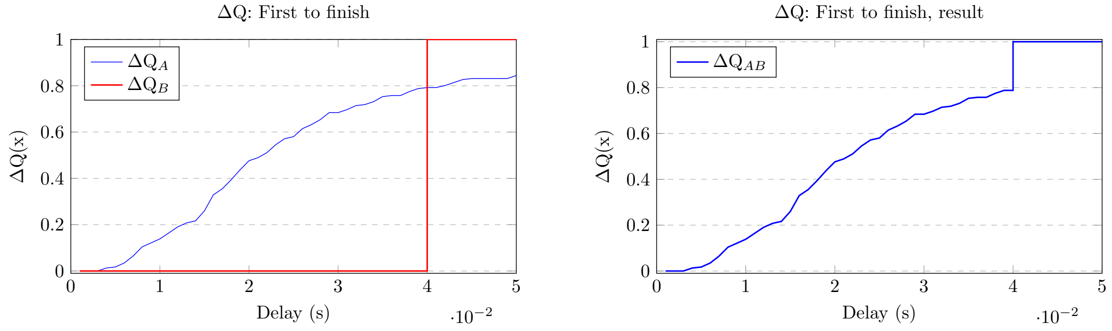


Figure 2.4: Left: Two ΔQs, A and B. Right: The result of the all to finish operator applied on A and B

All to finish

If we assume two independent outcomes O_A, O_B with the same start event, all-to-finish occurs when both end events occur, it can be calculated as:

$$\begin{aligned}\Delta Q_{ATF(A,B)} &= Pr[d_A \leq t \wedge d_B \leq t] \\ &= Pr[d_A \leq t] \cdot Pr[d_B \leq t] = \Delta Q_A \cdot \Delta Q_B \\ \Delta Q_{ATF(A,B)} &= \Delta Q_A \cdot \Delta Q_B\end{aligned} \tag{2.4}$$

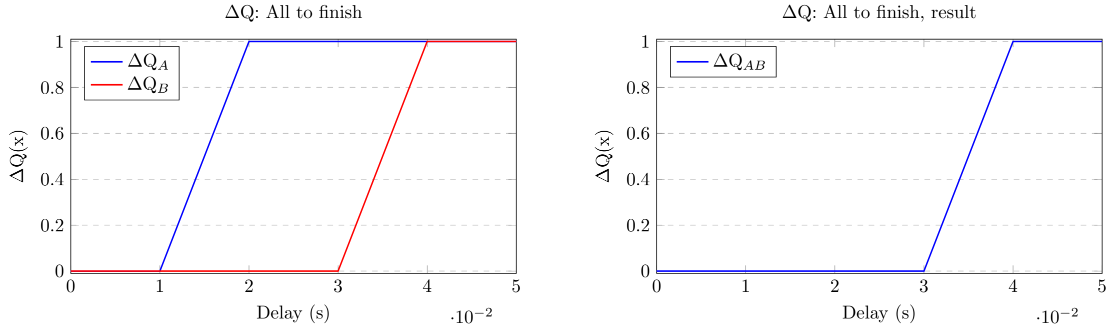


Figure 2.5: Left: Two ΔQs, A and B. Right: The result of the all to finish operator applied on A and B

Probabilistic choice

If we assume two possible outcomes O_A and O_B and exactly one outcome is chosen during each occurence of a start event and:

- O_A happens with probability $\dfrac{p}{p+q}$
- O_B happens with probability $\dfrac{q}{p+q}$

$$\Delta Q_{PC}(A, B) = \frac{p}{p+q}\Delta Q_A + \frac{q}{p+q}\Delta Q_B \tag{2.5}$$

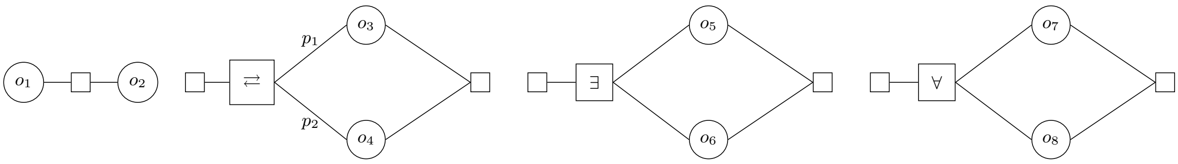


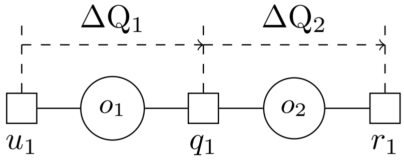
Figure 2.6: The possible relationships in an outcome diagram: Sequential composition, probabilistic choice, first-to-finish, all-to-finish

First-to-finish, All-to-finish and probabilistic-choice are calculated on the CDF of the ΔQ.

These outcome expressions can be assembled together to create an outcome diagram, later on, we will see how one can put translate the graphical representation to outcome diagrams which can be used in the ΔQ oscilloscope.

2.1.8 Independence hypothesis

Assume two sequentially composed outcomes o_1, o_2 running on the same processor. A probe p observing the execution from the start event of o_1 to the end event of o_2.



At low load, the two components behavior will be independent, the system will behave linearly, the observed delay of the probe p will be equal to the convolution of o_1, o_2 ($o_1 \circledast o_2$).

When load increases, the two components will start to show dependent behaviour due to the processor utilisation increasing, the observed ΔQ will then deviate from what is calculated.

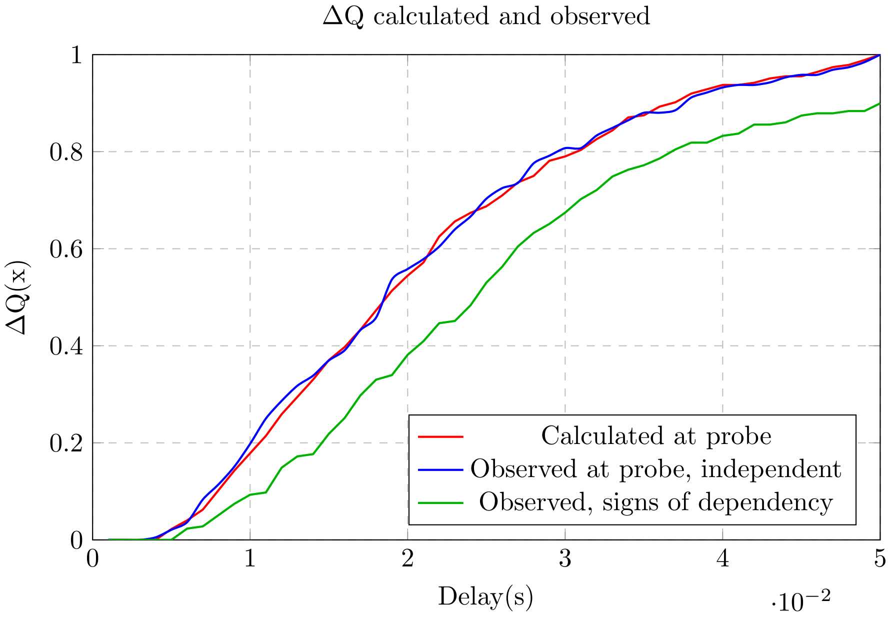


Figure 2.7: When the components are independent, what is observed (blue) and calculated (red) can be superposed, whilst when o_1 and o_2 show initial signs of dependency, what is observed (green) can be seen deviating from the calculated ΔQ.

When the system is far from being overloaded, the effect is noticeable thanks to ΔQSD even if the system is far from being overloaded. As the cliff edge of overload is approached, the nonlinearity will increase.

2.2 Observability

Observability refers to the ability to understand the internal state by examining its output, in the context of a distributed system, being able to understand the internal state of the system examining its telemetry data. [8]

In the case of the Erlang programming language, we explain below two tools that can be used to observe an Erlang program.

2.2.1 erlang:trace

The Erlang programming language gives the users different ways to observe the behaviour of the code, one of those is the function `erlang:trace/3`. The erlang run-time system exposes several trace points that can be observe, observing the trace points allows users to be notified when they are triggered [6]. One can observe function calls, messages being sent and received, process being spawned, garbage collecting ....

Nevertheless, Erlang Tracing, according to our use case, has a major flaw: no notion of causality. If two messages a, b are sent and then received in disorder, the tracer has no default way of knowing which is which, this is a missing feature that is crucial for observing a program functioning and being able to connect an application to our oscilloscope. This is where the OpenTelemetry standard comes in.

```
-spec trace(PidPortSpec, How, FlagList) -> integer()
   when
       PidPortSpec ::
           pid() |
           port() |
           all | processes | ports | existing | existing_processes |
            ↪  existing_ports | new |
           new_processes | new_ports,
       How :: boolean(),
       FlagList :: [trace_flag()].
```

Figure 2.8: erlang:trace\3 specification

2.2.2 OpenTelemetry

OpenTelemetry is an open-source, vendor agnostic observability framework and toolkit designed to generate, export and collect telemetry data, in particular traces, metrics and logs. [8]

OpenTelemetry is available for a plethora of languages, including Erlang, although, as of writing this, only traces are available in Erlang.

OpenTelemetry provides a standard protocol, a single set of API and conventions and lets you own the generated data, allowing to switch between observability backends freely.

The Erlang Ecosystem Foundation has a working group focused on evolving the tools related to observability.

Traces

Traces are why we are basing our program on top of OpenTelemetry, traces follow the whole "path" of a request in an application, traces are comprised of one or more spans.

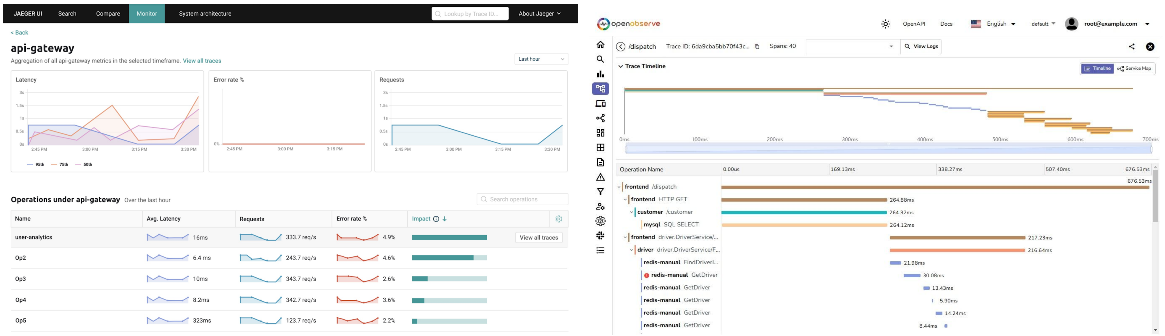
Span A span is a unit of work or operation. Spans can be correlated to each other and can be assembled into a trace. The notion of spans and traces allows us to follow the execution of a "request" and carry a context, allowing us to get the causal links of messages. [9]

```
{
  "name": "oscilloscope-span",
  "context": {
    "trace_id": "5b8aa5a2d2c872e8321cf37308d69df2",
    "span_id": "5fb397be34d26b51"
  },
  "parent_id": "0515505510cb55c13",
  "start_time": "2022-04-29T18:52:58.114304Z",
  "end_time": "2022-04-29T22:52:58.114561Z",
  "attributes": {
    "http.route": "some_route"
  },
}
```

Figure 2.9: Example of span with a parent, indicating a causal link between parent and children span [9]

Exporters

OpenTelemetry gives the possibility to export traces to backends such as Jaeger or Zipkin. A user can monitor their workflows, analyze dependencies, troubleshoot their programs by observing the flow of the requests in such backends. [10]



api-gateway

Aggregation of all api-gateway metrics in the selected timeframe. View all traces

Operations under api-gateway Over the last hour

Name	Avg. Latency	Requests	Error rate %	Impact
user-analytics	16ms	333.7 req/s	4.9%	
Op2	6.4 ms	243.7 req/s	4.6%	
Op3	10ms	343.7 req/s	2.6%	
Op4	8.2ms	342.7 req/s	3.6%	
Op5	323ms	123.7 req/s	2.2%	

(a) Jaeger interface [11].

/dispatch Trace ID: 6da9cba5bb70f43c... Spans: 40

Operation Name	0.00us	169.13ms	338.27ms	507.40ms	676.53ms
frontend /dispatch					676.53ms
frontend HTTP GET	264.88ms				
customer /customer	264.32ms				
mysql SQL SELECT	264.12ms				
frontend driver.DriverService/...			217.23ms		
driver driver.DriverService/F...			216.64ms		
redis-manual FindDriverI...			21.98ms		
redis-manual GetDriver			30.08ms		
redis-manual GetDriver			13.43ms		
redis-manual GetDriver			5.90ms		
redis-manual GetDriver			14.24ms		
redis-manual GetDriver			8.44ms		

(b) A span analysis on OpenObserve [12]

Macros

OpenTelemetry provides macros to start, end and interact with spans in Erlang. [13]

?with_span `?with_span` creates active spans. An active span is the span that is currently set in the execution context and is considered the "current" span for the ongoing operation or thread. [14]

```
parent_function() ->
    ?with_span(parent, #{}, fun child_function/0).

child_function() ->
```

```
    %% this is the same process, so the span parent set as the active
    %% span in the with_span call above will be the active span in
    ↪  this function
    ?with_span(child, #{},
               fun() ->
                   %% do work here. when this function returns, child
                   ↪  will complete.
               end).
```

?start_span `?start_span` creates a span which isn't connected to a particular process, it does not set the span as the current active span.

```
SpanCtx = ?start_span(child),
Ctx = otel_ctx:get_current(),
proc_lib:spawn_link(fun() ->
                        otel_ctx:attach(Ctx),
                        ?set_current_span(SpanCtx),
                        %% do work here
                        ?end_span(SpanCtx)
                    end),
```

?end_span `?end_span` ends a span started with `?start_span`

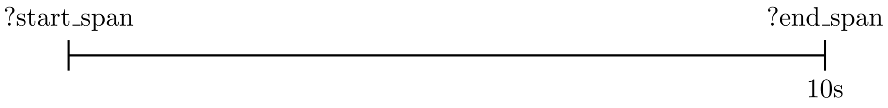
2.3 Current observability problems

A legitimate question would ask why one would need an additional tool to observe their system, observability tools are already plenty and provide useful insights into an application's behaviour.

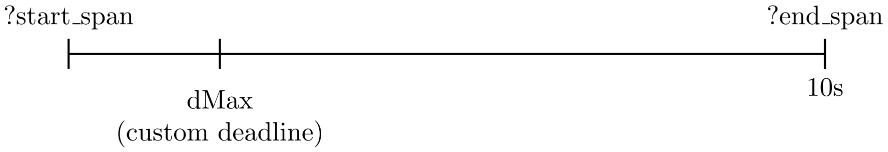
While they may seem adequate enough to provide a global oversight of applications, they fail to diagnose real time problems like overload, dependent behaviour early enough and in a quick manner.

The problem we are trying to tackle can be described by the following situation:

Imagine an Erlang application instrumented with OpenTelemetry, suddenly, the application starts slowing down, and the execution of a function takes 10 seconds, now, between its start and its end, the user instrumenting the application sees nothing in his dashboard.



This is a big problem! One would like to know right away if something is wrong with their application. This is where the ΔQSD paradigm and the ΔQ oscilloscope come in handy.



By extending ΔQSD notion of early failure one can now right away when the system is overloaded and showing problems, one can know right away when something is wrong, as soon as the maximum delay is hit, this avoids waiting, in this case, 10 seconds to know that something is wrong with your application.

2.3.1 Handling of long span

OpenTelemetry presents a bigger problem, what happens when there are long-running spans? Worse, what happens when spans are not actually terminated?

OpenTelemetry limits the length of OpenTelemetry spans, moreover, spans who are not terminated are lost and not exported. Why? All spans must be ended!

If the span is the parent/root spans, its effect could trickle down to child spans. We can quickly see how this becomes problematic, all the information about an execution of your program . . . lost. Moreover, a span could not be terminated for trivial reasons: refreshing a tab, network failures, crashes . . . [**otel-l**]. There are a few hacks that can be implemented, having shorter spans, carrying data in child spans, saving spans in a log to track spans which were not ended to manually set an end time.

These problems are a big limitation of OpenTelemetry, we believe that the wrapper we provide can be a great start to improve observability requirements in OpenTelemtry.

Chapter 3

Design

This chapter is divided into multiple sections:

- We first explain what the components that collaborate with the oscilloscope are.
- We then provide extensions of ΔQSD definitions, to fit the paradigm to work for our oscilloscope.
- Lastly, we explain the concept of triggers and snapshots, which make our ΔQ oscilloscope comparable to a real one.

3.1 Scenario

We can define four parts of interest for our tool.

System under test The system under test is the Erlang system the engineer wishes to observe, it ideally is a system which already is instrumented with OpenTelemetry. The ideal system where ΔQSD is more useful is a system that executes many independent instances of the same action.

Stub/wrapper The stub is the `otel_wrapper`, a wrapper that starts and ends OpenTelemetry spans, and start custom spans which are useful for the oscilloscope. Further handling of OpenTelemetry spans is delegated to the user, who may wish to do further operations with their spans.

The custom spans can be ended normally like OpenTelemetry spans or can timeout, given a custom timeout, and fail, according to user's definition of failure.

The stub is called from the system under test and communicates spans data to the oscilloscope via TCP.

The stub can receive messages from the oscilloscope, the messages are about updating observable's $dMax$.

Server The server is responsible for receiving the messages containing the custom spans from the oscilloscope. The server forwards the spans to the oscilloscope.

Oscilloscope The oscilloscope receives the custom spans from the stub and creates samples from said spans.

The oscilloscope has a graphical interface which allows the user to create an outcome diagram of the system under test, display real time graphs which show detail about the execution of the system and allow the user to set custom timeouts for observables.

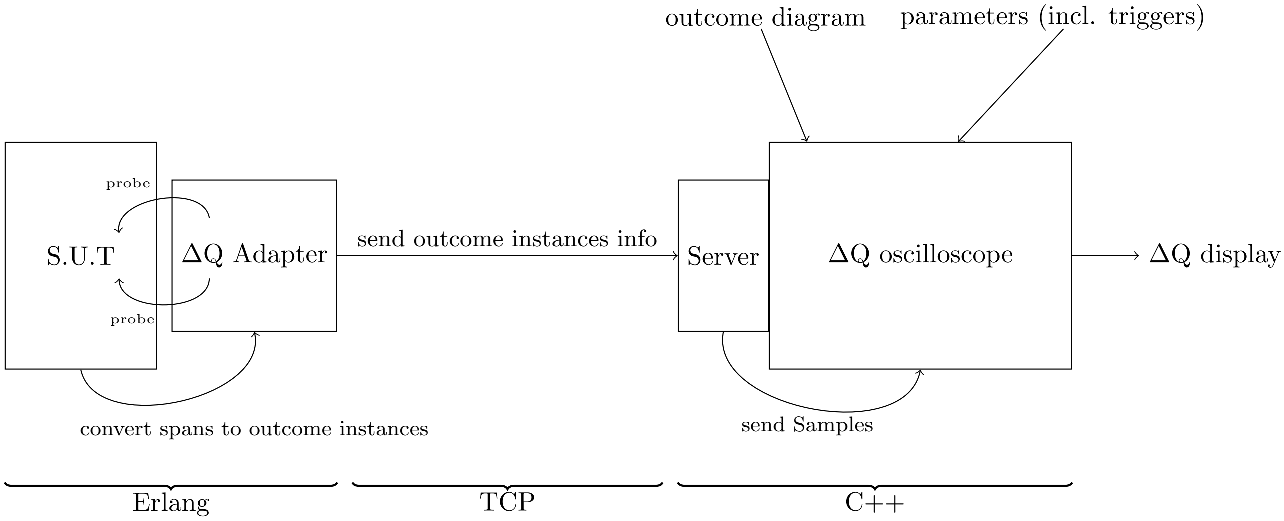


Figure 3.1: Global system diagram: the SUT calls the wrapper when starting, ending and failing spans. The spans are received by the server which processes them and sends them to the oscilloscope. The server communicates with the stub to update informations about the system under test ($dMax$)

3.2 Extending the notion of failure

Whilst previously we defined as "an input message m_{in} that has no output message m_{out}", we extend this definition. If you recall the introduction 2.3, we introduced the notion of a maximum delay.

We extend the notion of failure to the following definition:

"An input message m_{in} that has no output message m_{out} after x seconds"

Where x is defined by the user. We can leverage this new definition to observe ΔQs in real time.

3.3 Time series

Consider an observable O with two distinct sets of events, the starting set of events s and ending set of event e, the time series of an observable can be defined by n outcome instances s_i with the following structure:

- The probe's name
- The start time t_s
- The end time t_e
- Its status
- Its elapsed time of execution

The sample has three possible statuses: `success, timeout, failure`, it can thus be broken down in the representations, based on its status:

- $(t_s$,$t_e)$: This representation indicates that the execution was successful (t $<$ $dMax$).
- $(t_s, \mathcal{T})$: This representation indicates that the execution has timed out (t $>$ $dMax$).
- $(t_s, \mathcal{F})$: This representation indicates the execution has failed given a user defined requirement (i.e. a dropped message given buffer overload in a queue system). It must not be confused with a program failure (crash), if a program crashes during the execution of event e, it will timeout since the stub will not receive an end message. The end time is equal to $t_s +$ timeout

The ΔQ can then be modelled easily with n outcome instances by calculating its PDF and consequently the ECDF.

What can be considered a failed execution? Imagine a queue with a buffer: the buffer queue being full and dropping incoming messages can be modeled as a failure.

More generally, the choice of what is considered a failed execution is left up to the user who is handling the spans and is program-dependent. Exceptions, crashing, errors can be kinds of failure.

On another note, the way of handling errored spans in OpenTelemetry can differ from user to user, so the wrapper will not handle ending and setting statuses for "failed" spans.

3.4 Probes

To observe the system under test, the resulting outcomes, the result of causal links and outcome expressions, we must put probes in the system.

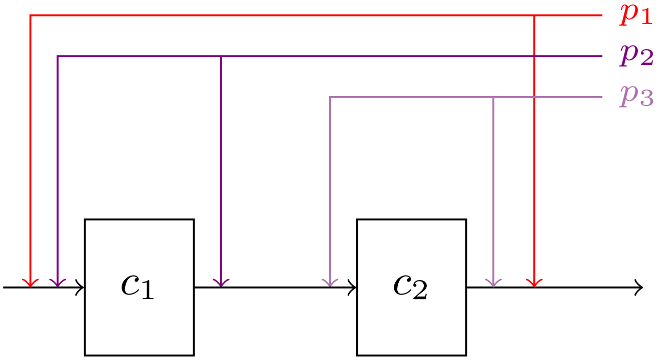
For each outcome of interest, a probe (observation point) is attached to measure the delay of the outcome, like one would in a true oscilloscope.

These probes allow to connect the system under test to the stub, which in turns sends outcome instances to the oscilloscope, which performs statistical computations on all the time series.

Consider the figure below, a probe is attached at every component to measure the delay of N outcome (p_2, p_3), the stub will send the outcome instance data for each probe observing an outcome to the oscilloscope, which will measure their respective ΔQs from the time series data and display them (if chosen by the user).

Another probe (p_1) is inserted at the beginning and end of the system to measure the global execution delay.

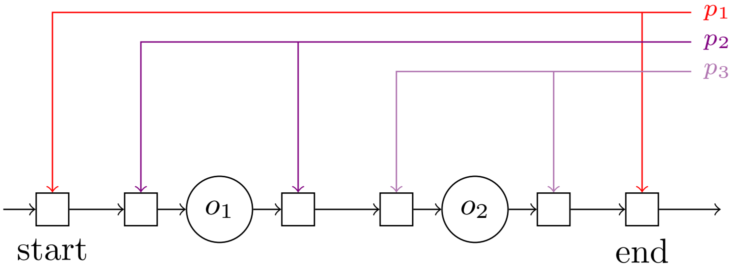
Thanks to this probe, the user can observe the ΔQ *"observed at p_1"*, which is the ΔQ which was calculated from the data received by inserting probe p_1. The ΔQ *"calculated at p_1"* is the resulting ΔQ from the convolution of the observed ΔQs at c_2 and c_3.



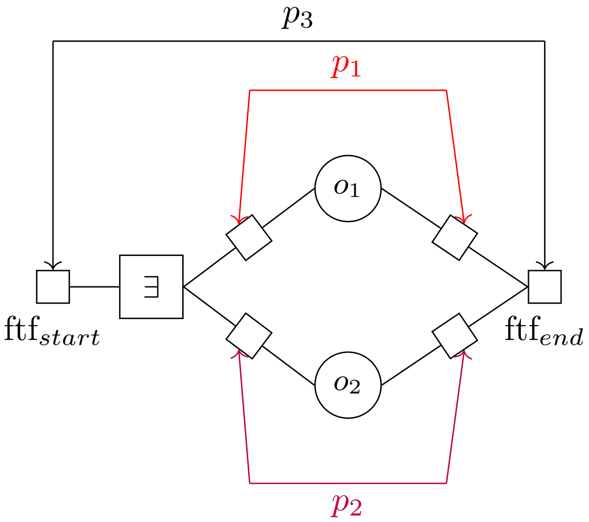
3.4.1 Inserting probes in the oscilloscope

Probes are automatically inserted in the oscilloscope when defining outcomes, part of the system the user wishes to observe and operators.

In the system below, which is equal to the one defined above, probes are automatically attached to outcomes o_1, o_2. The user who wants to observe the result of the sequential composition can insert probes at the start and end of the routine.



As for operators (outcome expression), probes are automatically attached to the components inside them and to the start event and end events of the operators.



The **observed ΔQ** for the first-to-finish operator is the ΔQ from the instances (**start**, **end**). The **calculated ΔQ** is the ΔQ which is the result of the first-to-finish operator being applied on o_1, o_2

3.4.2 Probes: from spans to outcome instances

OpenTelemetry spans are useful to carry context, attributes and baggage in a program, the plethora of attributes they have is nevertheless too much for the oscilloscope.

To get the equivalent of spans for the oscilloscope, the stub needs to be called at the starting events of a probe to start an instance, and at the ending events to end the outcome instance and send the data to the oscilloscope.

```
% Start the outcome instance of worker_2
{WorkerCtx, WorkerPid} = otel_wrapper:start_span(<<"worker_2">>),

% Do work here ...

%End the outcome instance of worker_2
otel_wrapper:end_span(WorkerCtx, WorkerPid),
```

3.5 Triggers

The concept of triggers is key to the oscilloscope, much like an oscilloscope that has a trigger mechanism that fires when a signal of interest is recognized by the oscilloscope, the ΔQ *oscilloscope* has a similar mechanism that can recognize when an observed ΔQ violates certain conditions regarding required behaviour.

Each time an observed ΔQ is calculated by the oscilloscope, it is checked against the requirements set by the user. If these requirements are not met, a trigger is fired and a snapshot of the system is saved to be shown to the user.

3.5.1 Snapshot

A snapshot of the system gives insights into the system before and after a trigger was fired. It gives the user a still of the system, as if it was frozen in time.

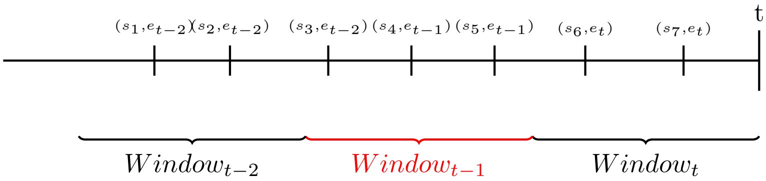
When an observed ΔQ is calculated for each component being observed in the oscilloscope, they are stored away. In case the probe is observing multiple components, the ΔQ which is the result of the outcome expressions is also stored.

If no trigger is fired, older observed (and calculated) ΔQs are removed. In the case that a trigger is fired, the oscilloscope keeps recording ΔQs without removing older ones, to allow the user to look at the state of the system before the trigger and after.

3.6 Polling window

To calculate a ΔQ, we take all the outcome instances that ended within a window of time from t_l to t_u, a lower and upper time bound.

Suppose we are at time t, the window we will display is the **window of time** $(t-1)_l$ **-** $(t-1)_u$ with $t-1$ equal to $t-x$, and x the polling rate. This is to account for various overheads that need to be taken into consideration, which could be network overhead, the wrapper overhead, C++ latency . . . Imagine multiple outcome instances that are ended at a time slightly lower but close to t, and due to the overheads the messages arrives at a time slightly higher but close to t, the outcome instance would not be taken into consideration for the calculation of a ΔQ.



The polling window then advances every x seconds setting the new window:

$$\text{From: } (t-1)_l,\ (t-1)_u \xrightarrow{t+1} t_l, t_u.$$
$$\text{Where: } t_l = (t-1)_u \text{ and } t_u = (t-1)_u + x$$

Chapter 4

Oscilloscope: User level concepts

The following chapter gives insights on the concepts of ΔQSD in the oscilloscope needed by the user to understand how the oscilloscope works.

- We first provide insights into how ΔQSD was implemented in the oscilloscope, the parameters that define a probe's ΔQ, its representation and what can be done with ΔQs. We show how a probe ΔQ will be shown in the oscilloscope
- We then provide a language to write outcome diagrams based on an already existing syntax.
- Lastly, we explain how to control the system in the oscilloscope and how to interact with the stub

4.1 ΔQSD implementation

Originally, ΔQ(x) denotes the probability that an outcome occurs in a time $t \leq x$, defining then the "intangible mass" of such IRV as $1 - \lim_{x \to \infty} \Delta Q(x)$. We then extend the original definition to fit real time constraints, needing to calculate ΔQs continuously.

For a given probe, ΔQ(t_l, t_u, $dMax$) is the probability that the time of series with samples between time $t_l < t_u$, an outcome or probe occurs in time t ≤ dMax.

4.1.1 Internal representation of a ΔQ

We provide a ΔQ class to calculate the ΔQ of a probe between a lower time bound t_l and an upper time bound t_u.

The ΔQ can be calculated in various ways:

Observed ΔQ The first way is by having n collected outcome instances between t_l and t_u, calculating its PDF and then calculating the *empirical cumulative distribution function* (ECDF) based on its PDF. This is called the **Observed ΔQ**.

Calculated ΔQ A ΔQ can also be calculated by performing operations which are the result of outcome expressions on two or more ΔQs, the notion of outcome instances is then lost between calculations, as the interest shifts towards calculating the resulting PDFs and ECDFs. This is called the **Calculated ΔQ**.

4.1.2 dMax

The key concept of ΔQSD is having a maximum delay after which we consider that the execution is failed, this is represented in a prove as $dMax$. The user defines, for each prove the maximum delay its execution can have.

Setting a maximum delay for an prove is not a job that can be done one-off and blindly, it is something that is done with an underlying knowledge of the system inner-workings and must be thoroughly fine tuned during the execution of the system by observing the resulting distributions of the obtained ΔQs.

We define in our oscilloscope a formula to dynamically define a maximum delay:

$$dMax = \Delta_T * N \tag{4.1}$$

Where:

- Δ_{tbase} represents the base width of a bin, equal to 1ms.
- N the number of bins.

The user must choose:

- Δ_T: Δ_T is a value which can be set via a slider on the dashboard to control the delay of a probe.
- N: We define a range $[1, 1000]$ for N. This is a good enough bound to allow for finer grained bins, or less precision if needed.

Some tradeoffs must though be acknowledged when setting these parameters, a higher number of bins corresponds to a higher number of calculations and space complexity, a lower $dMax$ may correspond to more failures. These are all tradeoffs that must be considered by the system engineer and set accordingly.

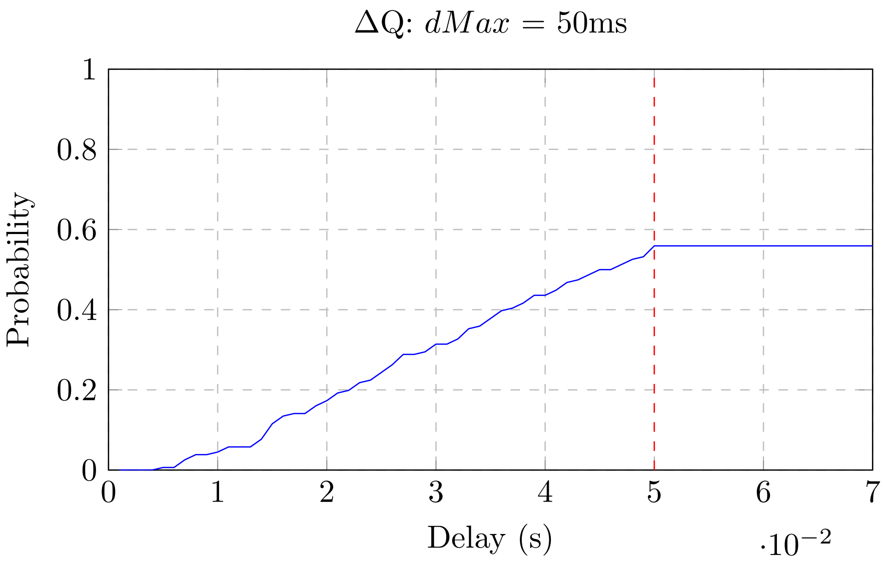


Figure 4.1: ΔQ: $dMax$ = 50ms, the CDF will stay constant when delay > $dMax$

4.1.3 QTA

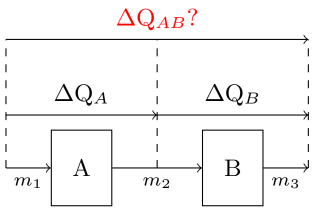
A simplified QTA is defined for probes. We define 4 points for the step function at 25, 50, 75 percentiles and the maximum amount of failures accepted for an observable. An observed ΔQ will calculate that based on the samples collected.

4.1.4 Operations

In a previous section we talked about the possible operations that can be performed on and between ΔQs, the time complexity of FTF, ATF and PC is trivially $\mathcal{O}(N)$ where N is the number of bins. As to convolution, the naïve way of calculating convolution has a time complexity of $\mathcal{O}(N^2)$, this quickly becomes a problem as soon as the user wants to have a more fine-grained understanding of a component. Below we present two ways to perform convolution.

Convolution

Convolution allows calculating the sum of delays of two causally linked ΔQ_A and ΔQ_B.



Arithmetical operations

We can apply a set of arithmetical operations between ΔQs ECDFs, and on a ΔQ.

Scaling (multiplication) A ΔQ can be scaled w.r.t a constant $0 \leq j \leq 1$. It is equal to binwise multiplication on ECDF bins.

$$\hat{f}_r(i) = \hat{f}(i) \cdot j \tag{4.2}$$

Operations between ΔQs Addition, subtraction and multiplication can be done between two ΔQ of equal bin width (but not forcibly of equal length) by calculating the operation between the two ECDFs of the ΔQs:

$$\Delta\mathrm{Q}_{AB}(i) = \hat{f}_A(i)[\cdot, +, -]\hat{f}_B(i) \tag{4.3}$$

4.1.5 Confidence bounds

To observe the stationarity of a system we must observe a window of ΔQs of an observable and calculate confidence bounds over said windows. The bounds can be updated dynamically by inserting or removing a ΔQ, this allows us to consider a small window of execution rather than observing the whole execution.

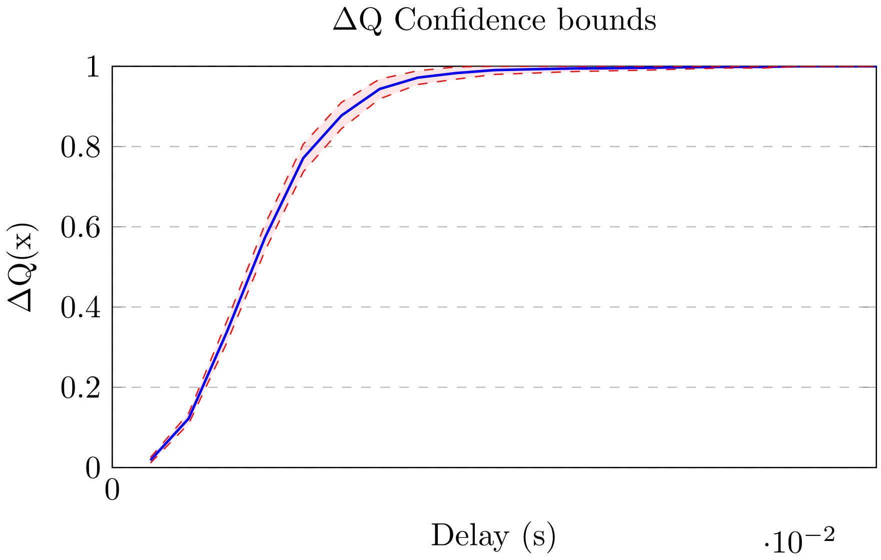


Figure 4.2: Upper and lower bounds of the mean of multiple ΔQs. In a system that behaves linearly, the bounds will be close to the mean, once the overload is approaching, or a system is showing behaviour that diverges from a linear one, the bounds will be larger.

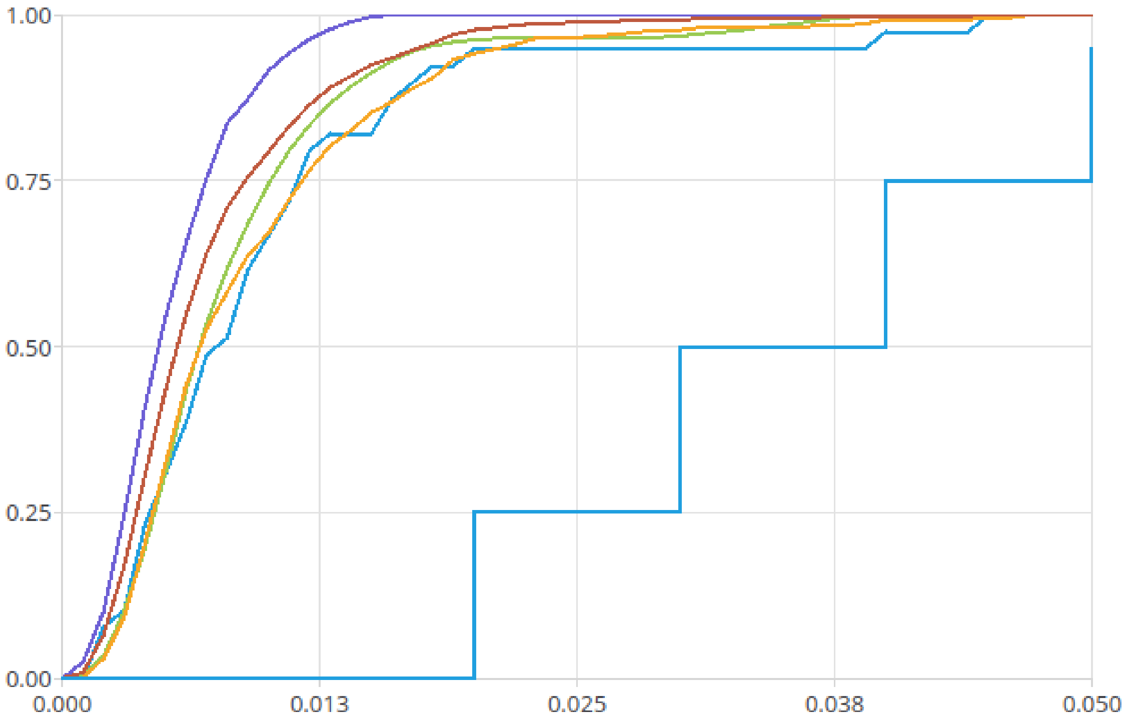
4.2 ΔQ display

An observable's displayed graph must contain the following functions:

- The mean and confidence bounds of a window of previous ΔQs
- The observed $\Delta\mathrm{Q}(t_l, t_u, dMax)$
- For a probe, the calculated ΔQ from its components.

- Its QTA

This allows for the user to observe if a ΔQ has deviated from normal execution, analyse its stationarity, nonlinearity and observe its execution.



4.3 Outcome diagram

An abstract syntax for outcome expressions and consequently outcome diagrams has already been defined in a previous paper [3], nevertheless, the oscilloscope provides additional features not included in the original syntax and, moreover, needs a textual way to define an outcome diagram.

We define thus a grammar to create an outcome diagram in our oscilloscope, our grammar is a textual interpretation of the abstract syntax.

4.3.1 Probes

To attach probes in the oscilloscope, the user must define outcomes and probes that observe outcome expressions.

Outcome

In our system an outcome is defined with its name

```
... = outcomeName;
```

Probes containing outcome expressions

A probe can contain one component or a sequence of causally linked components. The user can define as many probes that contain outcome expressions as they want, they have to be declared as follows:

```
probe = component [-> component2];
probe2 = newComponent -> anotherComponent;
```

These probes can be reused in other probes or in the system by adding `"s:"` (subsystem) before they are used.

```
probe3 = s:probe -> s:probe2;
```

4.3.2 Operators, outcome expressions

To build a system, we must define the relations between outcomes and outcome expressions, below is how they can be defined.

First-to-finish, all-to-finish and probabilistic choice must contain at least two components, this is because the operations to calculate the *calculated* ΔQ rely on using the CDF of the components that define the operator.

Causal link

A causal link between two components can be defined by a right arrow from `component_i` to `component_j`

```
component_i -> component_j
```

All-to-finish operator

An all-to-finish operator needs to be defined as follows:

```
a:name(component1, component2...)
```

First-to-finish operator

A first-to-finish operator needs to be defined as follows.

```
f:name(component1, component2...)
```

Probabilistic choice operator

A probabilistic choice operator needs to be defined as follows:

```
p:name[probability_1, probability_2, ... probability_i](component_1,
↪  component_2, ..., component_i)
```

In addition to being comma separated, the number of probabilities inside the brackets must match the number of components inside the parentheses. For n probabilites p_i, $0 < p_i < 1$, $\sum_{i=0}^{n} p_i = 1$

4.3.3 Limitations

Our system has a few limitations compared to the theoretical applications of ΔQ, namely, no cycles are allowed in the definition of a system.

```
probe = s:probe_2;
probe_2 = s:probe;
```

The above example is not allowed and will raise an error when defined.

4.4 Dashboard

The dashboard is devised of multiple sections where the user can interact with the oscilloscope, create the system, observe the behaviour of its components, set triggers.

4.4.1 Sidebar

The sidebar has multiple tabs, we explain here the responsibility of each one.

System/Plots tab

System creation In this tab the user can create its system using the grammar defined before, he can save the text he used to define the system or load it, the system is saved to a file with any extension, we nevertheless define an extension to save the system to, the extension `.dq`. If the definition of the input is wrong, he will be warned with a pop up giving the error the parser generator encountered in the creation of a system.

Adding a plot Once the system is defined, the user can choose the probes he wants to plot. They can select multiple probes per plot and display multiple plots on the oscilloscope window.

Parameters tab

In this tab, the user can define parameters for the probes they have defined.

Set a QTA The user is given the choice to set a QTA for a given observable, they have 4 fields where they can fill in which correspond to the percentiles and the maximum amount of failures allowed, they can change this dynamically during execution.

dMax, bins The user has a slider which goes from -10 to 10, where they can set the parameters we explained previously, n, the exponent of $\Delta_{tbase} \cdot 2^n$ and the bins N. When these informations are saved by the user, the new $dMax$ is transmitted to the stub and saved for the selected observable.

Triggers tab

In the triggers tab the user can set triggers and observe the snapshots of the system.

Set triggers The user can set which triggers to fire for the probes they desire, they are given checkboxes to decide which ones to set as active or not (by default, the triggers are deactivated).

Fired triggers Once a trigger is fired, the system start a timer, during which all probes start recording the observed ΔQs (and the calculated ones if applicable) without discarding older ones. Once the timer expires, the snapshot is saved for the user in the triggers tab. In the dashboard, it indicates when the trigger was fired (timestamp) and the name of the probe which fired it.

4.4.2 Stub controls

Below the sidebar, two buttons are present, these buttons communicate to the stub.

The **start stub** button sends a message to the stub, telling it to start sending spans. The **stop stub** button stops it.

Chapter 5

Oscilloscope implementation

The following chapter gives a more technical description of the oscilloscope.

- We first explain how the stub works, its API and the underlying mechanism that let us export outcome instances to the oscilloscope.
- Next we give a technical explanation of the parser generator we used to parse the outcome diagram syntax.
- Lastly, we briefly talk about the dashboard graphical framework.

5.1 ΔQSD implementation

A probe's ΔQ can be represented internally by a PDF and displayed as an ECDF. Here is how both can be calculated given n outcome instances.

PDF

We approximate the PDF of the observed random variable $\mathbf{X}$ via a histogram. We partition the values into N bins of equal width, this is required to ease future calculations. Given $[x_i, x_{i+1}]$ the interval of a bin i, where $x_i = i\Delta x$, and $\hat{p}(x_i)$ the value of the PDF at bin i, for n bins:

$$\begin{cases} \hat{p}(i) = \dfrac{n_i}{n}, \text{if } i \leq n \\ \hat{p}(i) = \hat{p}(n), \text{if } i > n \end{cases} \tag{5.1}$$

Where n_i the number of successful outcome instances whose elapsed time is contained in the bin i, n the total number of instances.

ECDF

The value $\hat{f}(x_i)$ of the ECDF at bin i with n bins can be calculated as:

$$\begin{cases} \hat{f}(i) = \sum_{j=1}^{i} \hat{p}(j), & \text{if } i \leq n \\ \hat{f}(i) = \hat{f}(x_n), & \text{if } i > n \end{cases} \tag{5.2}$$

5.1.1 dMax

We introduced $dMax$ in the previous section, we provide here the full equation that allows $dMax$ to be calculated:

$$dMax = \Delta_{tbase} * 2^n * N \tag{5.3}$$

Where:

- Δ_{tbase} represents the base width of a bin, equal to 1ms.
- N the number of bins.

5.1.2 Operations

In a previous section we talked about the possible operations that can be performed on and between ΔQs, the time complexity of FTF, ATF and PC is trivially $\mathcal{O}(N)$ where N is the number of bins. As to convolution, the naïve way of calculating convolution has a time complexity of $\mathcal{O}(N^2)$, this quickly becomes a problem as soon as the user wants to have a more fine-grained understanding of a component. Below we present two ways to perform convolution.

Convolution

Naïve convolution Given two ΔQ binned PDFs f and g, the result of the convolution $f \circledast g$ is given by

$$(f \circledast g)[n] = \sum_{m=0}^{N} = f[m]g[n-m] \tag{5.4}$$

Fast Fourier Transform Convolution FFTW (Fastest Fourier Transform in the West) is a C subroutine library [16] for computing the discrete Fourier Transform in one or more dimensions, of arbitrary input size, and of both real and complex data. We use FFTW in our program to compute the convolution of ΔQs. We adapt our script from an already existing one found on GitHub

Whilst the previous algorithm is far too slow to handle a high number of bins, convolution leveraging Fast Fourier Transform (FFT) allows us to reduce the amount of calculations to $\mathcal{O}(n\log n)$.

FFT and naïve convolution produce the same results in our program barring ε differences (around 10^{-18}) in bins whose result should be 0.

FFTs algorithms are plenty, the choice of the one to use is left up to the subroutine via the parameter `FFTW_ESTIMATE` [**fft**].

Arithmetical operations

We can apply a set of arithmetical operations between ΔQs ECDFs, and on a ΔQ.

Scaling (multiplication) A ΔQ can be scaled w.r.t a constant $0 \leq j \leq 1$. It is equal to binwise multiplication on ECDF bins.

$$\hat{f}_r(i) = \hat{f}(i) \cdot j \tag{5.5}$$

Operations between ΔQs Addition, subtraction and multiplication can be done between two ΔQ of equal bin width (but not forcibly of equal length) by calculating the operation between the two ECDFs of the ΔQs:

$$\Delta\text{Q}_{AB}(i) = \hat{f}_A(i)[\cdot, +, -]\hat{f}_B(i) \tag{5.6}$$

5.1.3 Confidence bounds

To observe the stationarity of a system we must observe a window of ΔQs of an observable and calculate confidence bounds over said windows. We present here the formulae required to give such bounds with 95% confidence level.

For a bin i and an ECDF j, the mean of the bin over a window is:

$$\mu_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij} \tag{5.7}$$

Where x_{ij} is a bin's i value for an ECDF j. Its variance:

$$\sigma_i^2 = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij}^2 - \mu_i^2 \tag{5.8}$$

The confidence intervals CI_i for a bin i can then be calculated as:

$$CI_i = \mu_i \pm z_{\alpha/2} \cdot \frac{\sigma_i}{\sqrt{n_i}} \tag{5.9}$$

5.1.4 Rebinning

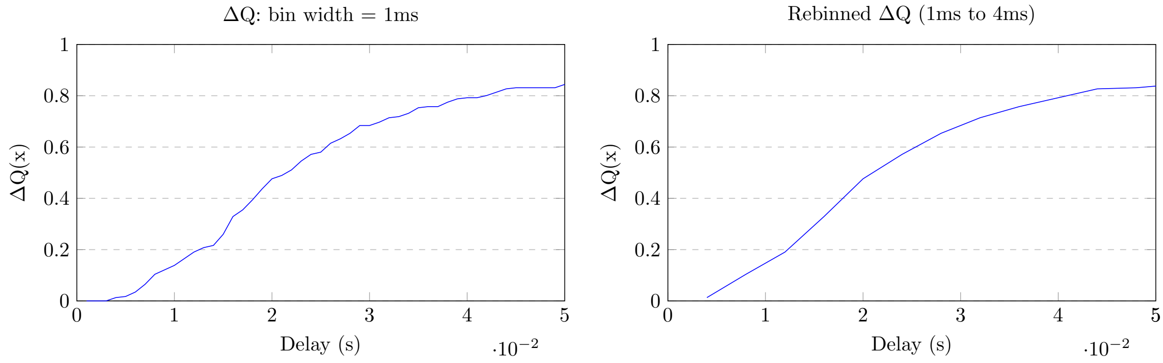
Rebinning refers to the aggregation of multiple bins of a bin width i to another bin width j. Operations between ΔQs can be done on ΔQs that have the same bin width, this is why it is fundamental that all probes have a common Δ_{tbase}. This allows for fast rebinning to a common bin width.
Given two ΔQs ΔQ_i, ΔQ_j:

$$\Delta_{Tij} = \max\,\{\Delta_{Ti}, \Delta_{Tj}\}$$

and the PDF of the rebinned ΔQ at bin b, from the original PDF of n bins, where $k = \frac{\Delta_T i}{\Delta_{Tj}}$:

$$p'_b = \sum_{n=b\cdot k}^{b+1\cdot k-1} p_n, \quad b = 0, 1, \ldots \lceil \frac{N}{k} \rceil \tag{5.10}$$

We perform rebinning to a higher bin width for a simple reason, while this leads to loss of information for the bin with the lowest bin width, rebinning to a lower bin width would imply inventing new values for the ΔQ with the highest bin width.



(a) Sample ΔQ with 1ms bins

(b) ΔQ on the left after rebinning to 4ms bins

5.2 Wrapper

The wrapper, called `dqsd_otel` is a rebar3 application built to replace OpenTelemetry calls and create custom spans, it is designed to be paired with the oscilloscope to observe an erlang application.

5.2.1 API

The wrapper functions to be used by the user are made to replace OpenTelemetry calls to macros as for `?start_span` and `?with_span` and `?end_span`. This is to make the wrapper less of an encumbrance for the user.
Moreover, the wrapper will always start OpenTelemetry spans but only start custom spans if the stub has been activated. The wrapper can be activated by: WIP

start_span/1, start_span/2

```
start_span/1: -spec start_span(binary()) -> {opentelemetry:span_ctx(),
↪  pid() | ignore}.
start_span/2: -spec start_span(binary(), map()) ->
↪ {opentelemetry:span_ctx(), pid() | ignore}.
```

Parameters:

- Name: Binary name of the observable
- Attributes: The OpenTelemetry span attributes (Only for start_span/2)

`start_span` incorporates OpenTelemetry `?start_span(Name)` macro.

Return: The function returns either:

- `{SpanCtx, span_process_PID}` if the wrapper is active and the observable's $dMax$ has been set
- `{SpanCtx, ignore}` if one of the two previous conditions was not respected.

With SpanCtx being the context of the span created by OpenTelemetry.

with_span/1, with_span/2

```
with_span/1: -spec with_span(binary(), fun(() -> any())) -> any().
with_span/2: -spec with_span(binary(), map(), fun(() -> any())) ->
↪  any().
```

Parameters:

- Name: Binary name of the observable
- Fun: Zero-arity function representing the code of block that should run inside the `?with_span` macro
- Attributes: The OpenTelemetry span attributes (Only for with_span/3)

`with_span` incorporates OpenTelemetry `with_span` macro.

Return: `with_span` returns what `Fun` returns (`any()`).

end_span

```
-spec end_span(opentelemetry:span_ctx(), pid() | ignore) -> ok |
↪  term().
```

Parameters:

- SpanCtx: The context of the span returned by `start_span`.
- Pid: `span_process_PID` || `ignore`

As is the case for `start_span`, `end_span` incorporates an OpenTelemetry macro, in this case `?end_span(Ctx)`.

fail_span

```
-spec fail_span( pid() | ignore) -> ok | term().
```

Parameter:

- Pid: `ignore` || `span_process_PID`

`fail_span` does not incorporate any OpenTelemetry macro, it is let up to the user to decide how to handle failures in execution.

span_process

`span_process` is the process, spawned by `start_span`, responsible for handling the `end_span, fail_span, timeout` messages.
Upon being spawned, the process starts a timer with time equal to the *dMax* set by an

user for the observable being observed, thanks to `erlang:send_after`. when the timer runs out, it sends a `timeout` message to the process. The process can receive three kinds of messages:

- `{end_span, end_time}`: This will send a custom span to the oscilloscope with the start and end time of the execution of the observable.
- `fail_span`: This will send a custom span to the oscilloscope indicating that an execution of an observable has failed.
- `timeout`: If the program hasn't ended the span before $dMax$, the timer will send a `timeout` message and it will send a custom span to the oscilloscope indicating that an execution of an observable has taken $> dMax$.

The process is able to receive one and only message, if the execution times out and subsequently the span is ended, the oscilloscope will not be notified as the process is defunct. This is assured by Erlang documentation:
If the message signal was sent using a process alias that is no longer active, the message signal will be dropped.

5.2.2 Handling outcome instances

To create custom spans of the outcome instances we must obtain three important informations:

- The name of the observed outcome or probe
- The time when the span was started
- The $dMax$ of the observed

They are all supplied upon starting a span with `otel_wrapper:[start_span, with_span]` by calling

```
StartTime = erlang:system_time(nanosecond),
```

The custom span is created only if two conditions are met: the wrapper has been set as active and the user set a timeout for the name of the observable, the functions will spawn a `span_process` process, passing along all the necessary informations.
Once the span is subsequently ended/timed out/failed, the function `send_span` creates a message carrying all the informations and sends it to the C++ server. The formatting of the messages is the following:

```
n:Observed name, b: Start time (beginning), e: End time (if end_span
↪  was received), s: The status
```

5.2.3 TCP connection

The wrapper is composed of two `gen_server` which handle communication to and from the oscilloscope. This gen_server behaviour allows the wrapper to send spans asynchronously to the oscilloscope.

TCP server

The TCP server listens by default on localhost at port 8081, the user can define a port and ip to listen at.

The oscilloscope can send commands to the stub, these commands are:

- `start_stub`: This command sets the stub as active, it can now send spans to the oscilloscope if the items are defined.
- `stop_stub`: This commands sets the stub as inactive, it will no longer send spans to the oscilloscope
- `set_timeout;probeName;timeout`: This command indicates to the stub to set the $dMax$ for a probe to timeOut, a limit of the stub is that erlang:send_after does not accept floats as timeouts, so the timeout will be rounded to the nearest integer

TCP client

The TCP client allows the stub to send the spans to the oscilloscope, by default the oscilloscope is on localhost:8080, but that can be changed by the user.

The client connects over TCP to the oscilloscope and opens a socket where it can send the spans.

5.3 Parser

To parse the system, we use the C++ ANTLR4 (ANother Tool for Language Recognition) library.

5.3.1 ANTLR

ANTLR is a parser generator for reading, processing, executing or translating structured text files. ANTLR generates a parser that can build and walk parse trees [17].
ANTLR is just one of the many parsers generators available in C++ (flex/bison, lex, yacc), although it presents certain limitations, its generated code is simpler to handle and less convoluted with respect to the other possibilities.
ANTLR uses Adaptive LL(*) *(ALL(*))* parser, namely, it will move grammar analysis to parse-time, without the use of static grammar analysis. [18]

5.3.2 Grammar

ANTLR provides a yacc-like metalanguage to write grammars. Below, is the grammar for our system: [cite]

```
grammar DQGrammar;

PROBE_ID: 's';
BEHAVIOR_TYPE: 'f' | 'a' | 'p';
```

```
NUMBER: [0-9]+('.'[0-9]+)?;
IDENTIFIER: [a-zA-Z_][a-zA-Z0-9_]*;
WS: [ \t\r\n]+ -> skip;

// Parser Rules
start: definition* system? EOF;

definition: IDENTIFIER '=' component_chain ';';
system: 'system' '=' component_chain ';'?;

component_chain
    : component ('->' component)*
;

component
    : behaviorComponent
    | probeComponent
    | outcome
;

behaviorComponent
    : BEHAVIOR_TYPE ':' IDENTIFIER ('[' probability_list ']')? '('
    ↪  component_list ')'
;

probeComponent
    : PROBE_ID ':' IDENTIFIER
;

probability_list: NUMBER (',' NUMBER)+;
component_list: component_chain (',' component_chain)+;

outcome: IDENTIFIER;
```

Limitations

A previous version was implemented in Lark[cite], a python parsing toolkit. The python version was quickly discarded due to a more complicated integration between Python and C++. Lark provided Earley(SPPF) strategy which allowed for ambiguities to be resolved, which is not possible in ANTLR.
For example the following system definition presents a few errors:

```
probe = s -> a -> f -> p;
```

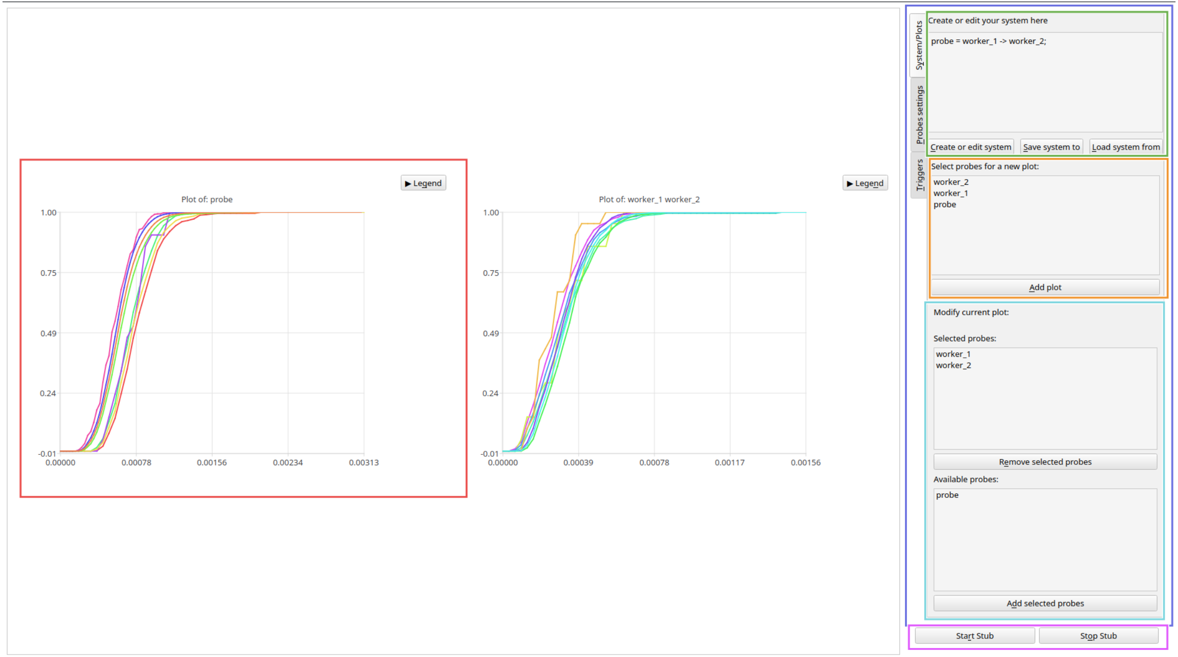
While Lark could correctly guess that everything inside was an outcome, ANTLR expects ":" after "s, a, f" and "p", thus, one can not name an outcome by these characters, as the parsers generator thinks that an operator or a probe will be next.

5.4 Oscilloscope GUI

Our oscilloscope graphical interface has been built using the QT framework for C++. Qt is a cross-platform application development framework for creating graphical user interfaces. We chose Qt as we believe that it is the most documented and practical library for GUI development in C++, using Qt allows us to create usable interfaces quickly, while being able to easily pair the backend code of C++ to the frontend.

The interface is composed of a main window, where widgets can be attached to it easily. Everything that can be seen is customisable widgets. This allows for easy reusability, modification and removal without great refactoring due in other parts of the system.

In the photo below we can see each top level widget (a QWidget that contains other widgets) in the main window, the widgets could easily be switched to other places of the window or rearranged.



```
probe = worker_1 -> worker_2;
```

Figure 5.2: The oscilloscope displaying probes, the boxes represent a top level widget, which may contain other widgets inside.

Chapter 6

Application on synthetic programs

This section aims to provide an example of how the oscilloscope could be used to instrument an application, in this case, a synthetic one. We explain how the ΔQSD paradigm can be applied to explore tradeoffs in design and to gain more insights into a running system.

6.1 M/M/1/K queue

We devised a simple Erlang system that can act as a simple M/M/1/K.

Why M/M/1/K? An average component in a distributed system can be modeled as an M/M/1/K, due to the exponential inter-arrival rate of messages, the exponential distribution of the execution delay and the message buffer size of a component.

The system has two components `worker_1`, `worker_2`, the components are made of a buffer queue of size K and a worker process.

The system sends n messages per second following a Poisson distribution to `worker_1`'s queue, the queue then reduces its available buffer size.

The buffer notifies its worker, which then does N loops, which are defined upon start, of fictional work. The worker then passes a message to `worker_2`'s queue, which has another queue of same size, who passes the message to `worker_2`'s worker, which does the same amount of loops. When a worker completes its work, it notifies the queue, freeing one "message" from its buffer size.

If the queue's buffer is overloaded, it will drop the incoming message and consider the execution a failure.

A probe p is defined, which observes the execution from when the first message up until `worker_2` is done.

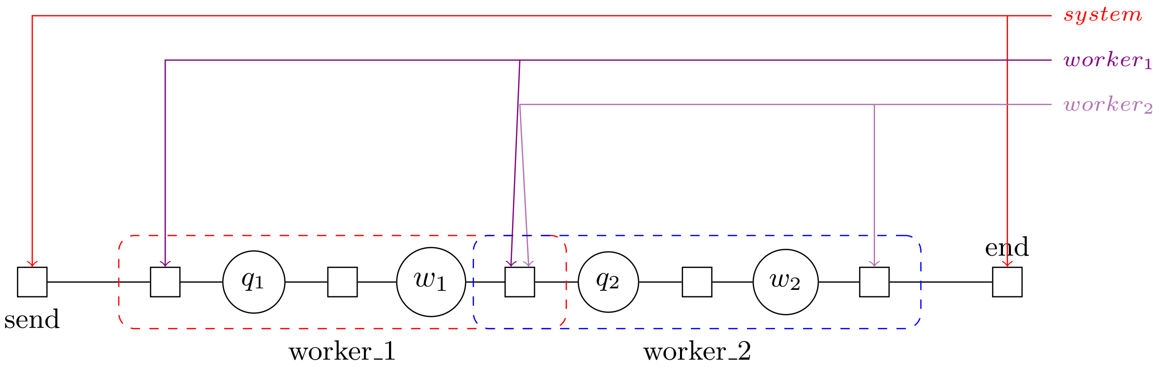


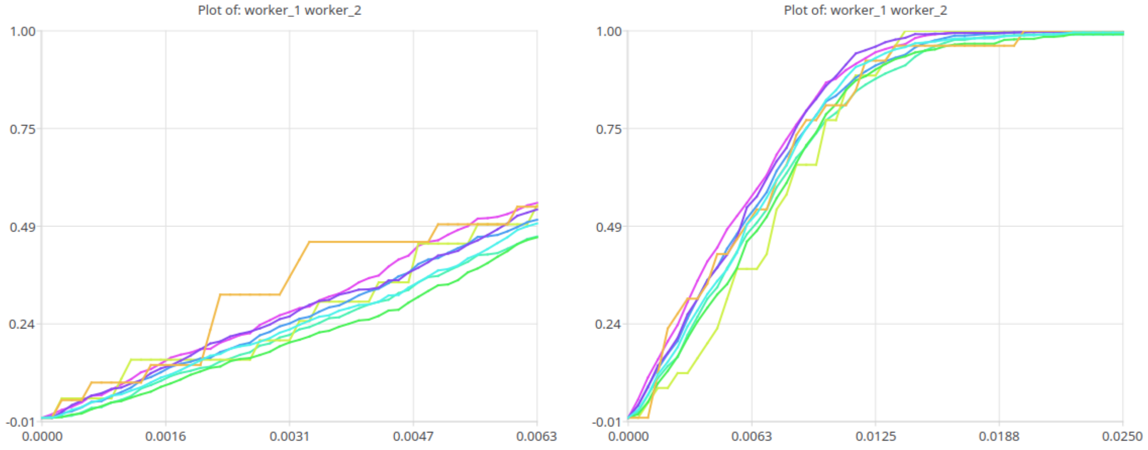
Figure 6.1: Outcome diagram of the M/M/1/K queue with the colored lines representing the probes that were inserted.

6.1.1 Determining parameters dynamically

We stated previously that determining parameters is something that must be done with an underlying knowledge of the system. The oscilloscope can provide knowledge of the system, here is an example of worker_1 and worker_2 as observed in the oscilloscope.

Imagine the engineer supposes the workers executions should take around 6.5 ms to complete, but doesn't actually know how long the executions should take. The engineer, after having set the required parameters observes in the following graph in the oscilloscope **??**.

The oscilloscope shows the engineer that their assumptions do not correspond to the actual system ΔQ, the user can then modify the parameters to observe the actual system's behaviour. By setting *dmax* to 25 ms, he can observe the worker's ΔQs approaching 1.



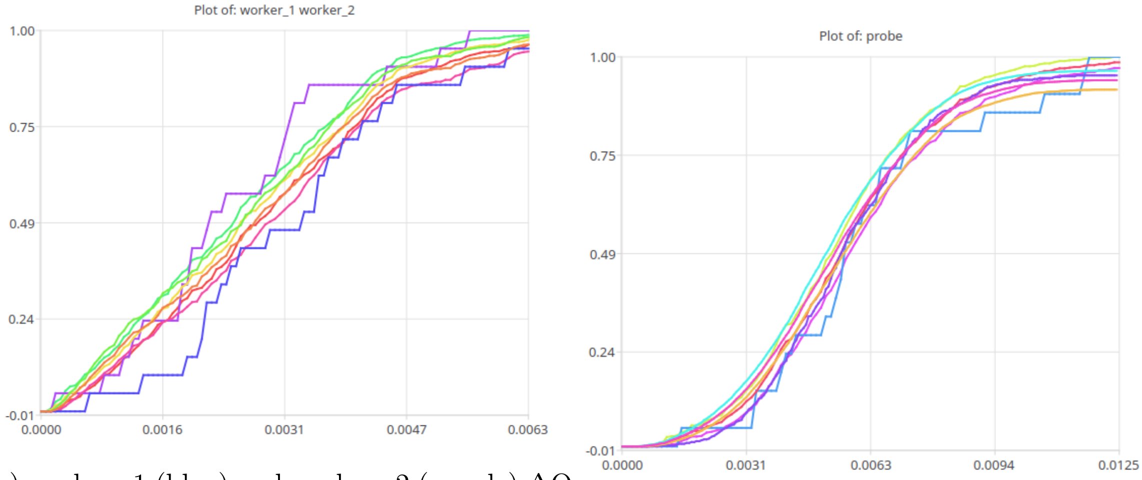
(a) worker_1 and worker_2 ΔQs plot with 6.5 ms $dMax$.

(b) worker_1 and worker_2 ΔQs plot with 25 ms $dMax$

On the other hand, the engineer's assumption could have been what he truly expected from the system, in this case, the oscilloscope tells him that the system is not behaving as expected.

Low Load At low load, we can observe in the oscilloscope how worker_1 and worker_2 mean ΔQs overlap. This is expected, even under overload or dependency conditions, worker_1 and worker_2 should have the same ΔQs.

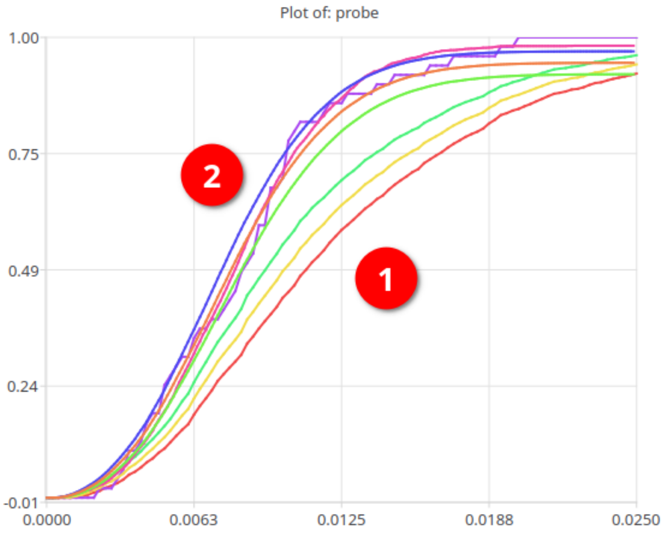
If the system is not showing dependent behaviour, the probe **observed ΔQ** and **calculated ΔQ** should overlap. We can observe that in the graph below, as the mean CDF of both ΔQs overlap.



(a) worker_1 (blue) and worker_2 (purple) ΔQ plots as shown in the oscilloscope

(b) probe ΔQ plots as shown in the oscilloscope

Early signs of overload Once the system is approaching overload, we can see the two means starting to diverge. As shown in a previous chapter, the observed (1) ΔQ of the probe is below the calculated (2) ΔQ. (explain better)



6.2 First to finish application

Next, we provide a synthetic application modeling an application that can be modeled by a first to finish operator

Why first to finish? Recall the previous FTF graph 2.4. Assume a send request to "the cloud" that waits for a response or a timeout, it is modeled by a FTF operator. A sample resulting graph of "the cloud" is the one we showed previously.

[INSRET PGRAH]

6.2.1 Using the wrong operator

What happens if the wrong operator is chosen to represent the causal relationships between the outcomes? What if the user believes that the system diagram is the one we presented before 6.1? The result on the oscilloscope will clearly show that something is wrong!

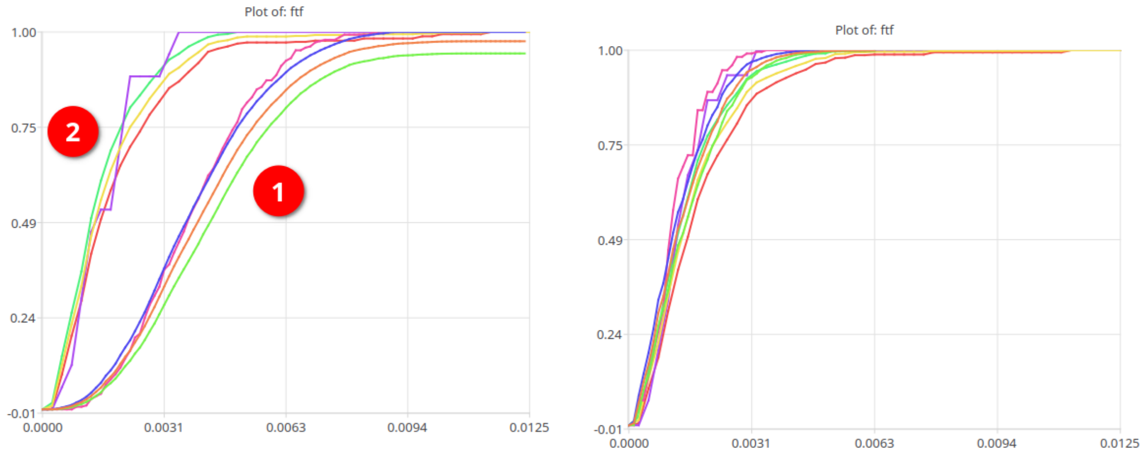


Figure 6.4: *(Left)* FTF plot **with wrong outcome diagram definition** as shown in the oscilloscope. (1) Observed ΔQ. (2) Calculated ΔQ.
(Right) FTF plot **with correct outcome diagram definition** as shown in the oscilloscope. Observed ΔQ and calculated ΔQ overlapping.

On the left, we can observe how the **calculated ΔQ** (2) is clearly less than the **observed ΔQ** (1). A difference this drastic tells us that the proposed outcome diagram does not correctly represent the actual system. On the right, if no dependencies are present and the correct operator is chosen, the two graphs will overlap.

Chapter 7

Performance study

This chapter evaluates the components and operations we introduced in previous sections, analysing their performances

7.1 Convolution performance

We implemented two versions of the convolution algorithm as described before, the naïve version and the FFT version. We compared their performance when performing convolution on two ΔQs of equal bins.

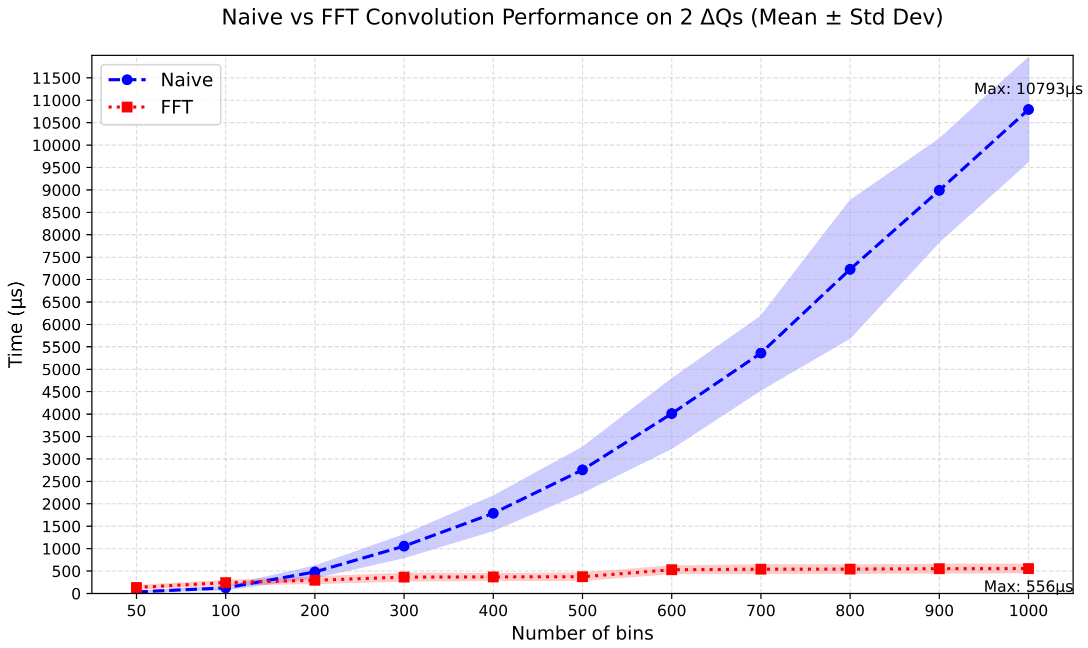


Figure 7.1: Performance comparison of two convolution algorithms

As expected, the naïve version has a time complexity of $\mathcal{O}(n^2)$ and quickly scales with the number of bins, this is clearly inefficient, as a more precise ΔQ will result in a much slower program.

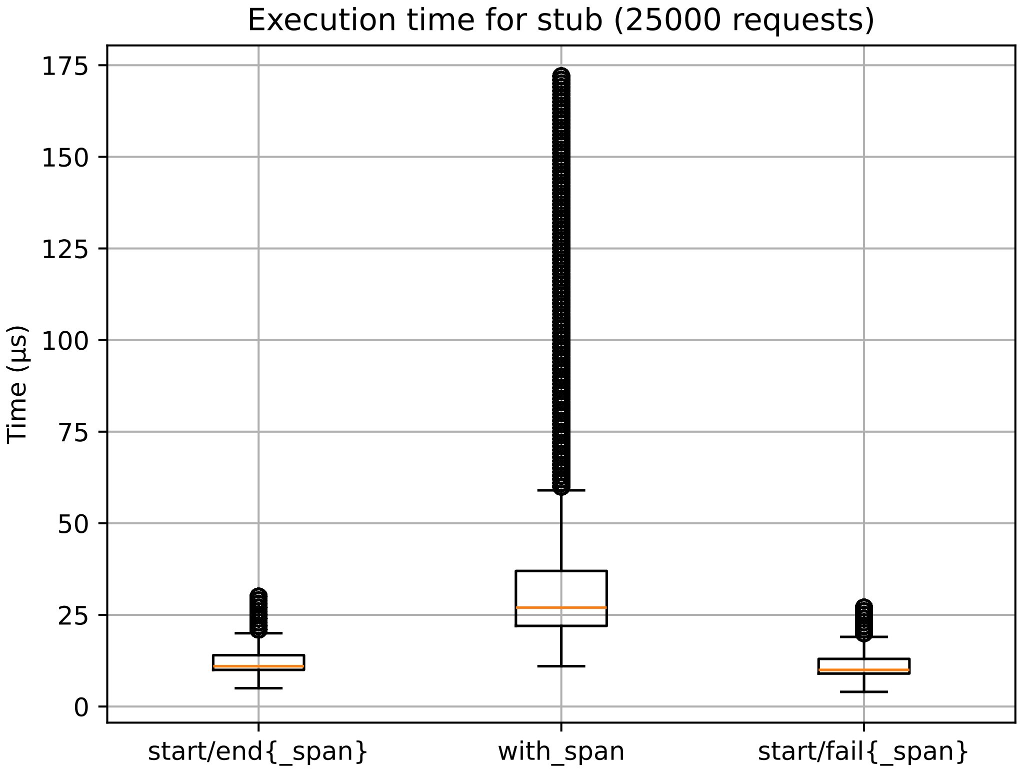
As for the FFT algorithm, it is slightly slower when the number of bins is lower than 100. This is due to the FFTW3 routine having slightly higher overhead.

7.2 Stub performance

We evaluated the performance of the stub to measure its impact in a normal execution, namely we tested the following calls which represent a normal usage of the wrapper.

- `start_span` → `end_span`.
- `with_span` with the following function: `fun() → ok`.
- `start_span` → `fail_span`.

We ran the simulation for 25000 subsequent iterations, these are the results.



Chapter 8

Conclusions and future work

The following project is the beginning of the ΔQ oscilloscope, our initial goal was to create an application to observe running distributed applications, namely, Erlang ones. A prototype was successfully created thanks to the following feats:

- The graphical dashboard for the ΔQ oscilloscope, built in C++, which allows real time display of ΔQs for the probes inserted in the system.
- Fast convolution algorithms to perform statistical analysis on probes.
- The creation of a textual syntax to create outcome diagrams.
- The `dqsd_otel` Erlang wrapper to connect an OpenTelemetry instrumented Erlang app to the oscilloscope.

The user has full control over the system and can update it dynamically to add or remove probes, this allows full control of what the user decides to include, allowing a finer grained outcome diagram or a more general view of the system.

The oscilloscope and the Erlang can communicate via TCP socket connections to exchange outcome instances and probe parameters,

We showed how it can be useful in detecting early signs of overload many crucial features are still missing from the dashboard and it could require less code modifications in the Erlang side.

8.1 Future improvements

We believe the oscilloscope and the Erlang application can be drastically improved, the size of the project and its intended goal is too big to be encompassed in a single master thesis. We list here some improvements which could be made to both the oscilloscope and the wrapper.

8.1.1 Oscilloscope improvement

- The oscilloscope could be turned into a **web app**, we feel that a C++ oscilloscope is a good prototype and proof of concept, but its usability would be greater in a browser context. It would be great as a plugin for already existing observability platforms like Grafana.
- A wider selection of **triggers**, as of writing this thesis, only the QTA trigger is available, this is a limitation due to time constraints. Nevertheless, triggers can be easily implemented in the available codebase.
- **Better communication between stub - server - oscilloscope**. The current way of sending outcome instances may be a limiting factor under high load, if hundred of thousands of spans were to be sent, the current way the server and oscilloscope are tied together may throttle communications. TCP socket connections could quickly become the chokepoint which makes the oscilloscope temporarily unusable.

  Future improvements on the server side could implement epoll system server calls to make the server more efficient; **Detaching server from client**, as of right now, the oscilloscope and the server are tied together, using ZeroMQ to assure real time server-client communications could be an interesting solution to explore.
- **Improve real time graphs**. The class QtCharts does not perform correctly with high frequencies update. Moreover, since we are plotting multiple series (from a minimum 4 to a maximum of 9) per probe, which allows up to 1000 bins per probe, the performance quickly degrades with more probes being displayed. A better graphing class for Qt could definitely improve the experience.
- **Saving probe parameters**: As of writing this thesis, there is no way to save the parameters one may have set.
- **Deconvolution**: An important aspect of ΔQSD, which was not introduced in this paper is deconvolution. It is used to check for infeasability in system desing. Since convolution has already been implemented, this could be integrated using the FFTW3 library.

8.1.2 Wrapper improvements

- As suggested by Bryan Naegele, a member of the observability group of Erlang, the wrapper, instead of working on top of OpenTelemetry, could be directly included inside the context of a span by using the ctx library [19], which provides deadlines for contexts, propagating the value in otel_ctx, making it available to the OpenTelemetry span processor. Leveraging `erlang:send_after` as we already do, we could create outcome instances with telemetry events to handle successful executions and timeouts. The span processor will then be responsible for creating outcome instances, without creating the need for custom functions in the wrapper, like we have now.

8.1.3 Real applications

A flaw of the oscilloscope and wrapper is that they have not been tested on real applications, while their usefulness has been proven on synthetic applications, the lack of real life applications is a weakness.

8.1.4 Licensing limitations

Lastly, a notable limitation is created by **Qt**, namely, QtCharts. The usage of Qt does not allow us to release our project under BSD/MIT licenses, but rather a GPLv3 one (we cannot release it under LGPL due to QtCharts).

Bibliography

[1] Peter Van Roy and Seyed Hossein Haeri. *The ΔQSD Paradigm: Designing Systems with Predictable Performance at High Load. Full-day tutorial.* 15th ACM/SPEC International Conference on Performance Engineering. 2024. URL: `https://webperso.info.ucl.ac.be/~pvr/ICPE-2024-deltaQSD-full.pdf`.

[2] Seyed H. Haeri et al. "Mind Your Outcomes: The ΔQSD Paradigm for Quality-Centric Systems Development and Its Application to a Blockchain Case Study". In: *Comput.* 11.3 (2022), p. 45. DOI: `10.3390/COMPUTERS11030045`. URL: `https://doi.org/10.3390/computers11030045`.

[3] Seyed Hossein Haeri et al. "Algebraic Reasoning About Timeliness". In: *Proceedings 16th Interaction and Concurrency Experience, ICE 2023, Lisbon, Portugal, 19th June 2023.* Ed. by Clément Aubert et al. Vol. 383. EPTCS. 2023, pp. 35–54. DOI: `10.4204/EPTCS.383.3`. URL: `https://doi.org/10.4204/EPTCS.383.3`.

[4] Peter Van Roy. *LINFO2345 lessons on ΔQSD.* Accessed: (19/05/2025). UCLouvain, 2023. URL: `https://www.youtube.com/watch?v=tF7fbU9Gce8`.

[5] Davies N. and Thompson P. *ΔQSD workbench - GitHub.* Accessed: (19/05/2025. 2022. URL: `https://github.com/DeltaQ-SD/dqsd-workbench`.

[6] Erlang programming language. *Erlang tracing.* Accessed: (19/05/2025). 2024. URL: `https://www.erlang.org/doc/apps/erts/tracing.html`.

[7] OpenTelemetry. *OpenTelemetry in Erlang/Elixir.* Accessed: (19/05/2025). 2025. URL: `https://opentelemetry.io/docs/languages/erlang/`.

[8] OpenTelemetry. *What is OpenTelemetry?* Accessed: (19/05/2025). 2025. URL: `https://opentelemetry.io/docs/what-is-opentelemetry/`.

[9] OpenTelemetry. *OpenTelemetry - Traces.* Accessed: (19/05/2025). 2025. URL: `https://opentelemetry.io/docs/concepts/signals/traces/`.

[10] The Jaeger Authors. *Jaeger.* Accessed: (19/05/2025). 2025. URL: `https://www.jaegertracing.io/`.

[11] Dotan Horovits. *From Distributed Tracing to APM: Taking OpenTelemetry & Jaeger Up a Level.* Accessed: (19/05/2025). 2021. URL: `https://logz.io/blog/monitoring-microservices-opentelemetry-jaeger/`.

[12] Sampath Siva Kumar Boddeti. *Tracing Made Easy: A Beginner's Guide to Jaeger and Distributed Systems.* Accessed: (19/05/2025). 2024. URL: `https://openobserve.ai/blog/tracing-made-easy-a-beginners-guide-to-jaeger-and-distributed-systems/`.

[13] OpenTelemetry. *Instrumentation for OpenTelemetry Erlang/Elixir.* Accessed: (19/05/2025). 2025. URL: `https://opentelemetry.io/docs/languages/erlang/instrumentation/`.

[14] OpenTelemetry. *Active spans, C++ Instrumentation.* Accessed: (19/05/2025). 2025. URL: https://opentelemetry.io/docs/languages/cpp/instrumentation/.

[15] Peter Thompson and Rudy Hernandez. *Quality Attenuation Measurement Architecture and Requirements.* Tech. rep. MSU-CSE-06-2. Sept. 2020. URL: https://www.broadband-forum.org/pdfs/tr-452.1-1-0-0.pdf.

[16] FFTW3. *Fastest Fourier Transform in The West.* Accessed: (19/05/2025). 2025. URL: https://www.fftw.org/.

[17] ANTLR. *What is ANTLR4?* Accessed: (19/05/2025). 2025. URL: https://www.antlr.org/.

[18] Terence Parr and Kathleen Fisher. "LL(*): the foundation of the ANTLR parser generator". In: *Proceedings of the 32nd ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI 2011, San Jose, CA, USA, June 4-8, 2011.* Ed. by Mary W. Hall and David A. Padua. ACM, 2011, pp. 425–436. DOI: 10.1145/1993498.1993548. URL: https://doi.org/10.1145/1993498.1993548.

[19] Tristan Sloughter. *ctx.* Accessed: (21/05/2025). 2023. URL: https://github.com/tsloughter/ctx.

Appendix A

User manual

A.1 Sidebar: Outcome diagram and plots

A.1.1 Creating the system

You need to provide a textual description of your outcome diagram following the syntax which was defined previously. You can create your system by clicking on the **Create or edit system** button. If the parser successfully parsed the text, your system will be created and you can start setting the parameters for your probes.

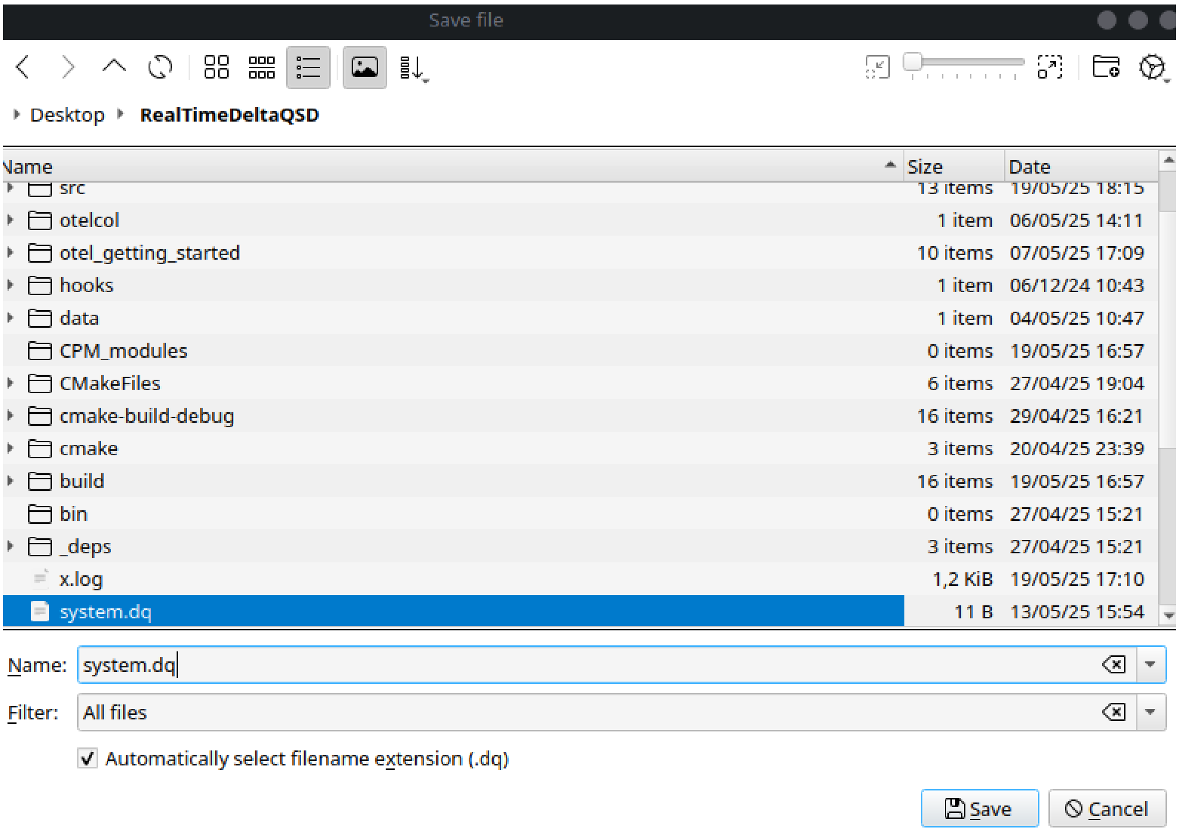
If the parser does not correctly parse the text, it will show a popup indicating the line where the error was produced and what it was expecting.

A.1.2 Saving the system definition

The button **Save system to** gives you the possibility to save the textual definition of the outcome diagram to a file, you can save the file to any extension, but preferably the file will have the **.dq** extension.

A.1.3 Loading the system definition

The button **Load system to** gives you the possibility to load the textual definition of the outcome diagram you may have previously saved to a file, as for saving, you can load any file extension.



Name	Size	Date
src	13 items	19/05/25 18:15
otelcol	1 item	06/05/25 14:11
otel_getting_started	10 items	07/05/25 17:09
hooks	1 item	06/12/24 10:43
data	1 item	04/05/25 10:47
CPM_modules	0 items	19/05/25 16:57
CMakeFiles	6 items	27/04/25 19:04
cmake-build-debug	16 items	29/04/25 16:21
cmake	3 items	20/04/25 23:39
build	16 items	19/05/25 16:57
bin	0 items	27/04/25 15:21
_deps	3 items	27/04/25 15:21
x.log	1,2 KiB	19/05/25 17:10
system.dq	11 B	13/05/25 15:54

Name: system.dq

Filter: All files

☑ Automatically select filename extension (.dq)

A.1.4 Managing the plots

Once you have your system defined you can start adding plots of the ΔQs of the probes you inserted in your system.

Adding a plot

Multiple probes can be added at once in your plot, you can select the probes you want to add to a new plot by selecting them in the **"Add a new plot"** section. Then by clicking the **"Add plot"** button, the selected probes will be added to the plot.

Editing a plot

You can remove the probes you have added to the plot by first clicking to it, this sets the plot as the **selected plot**. Once you have clicked the plot, a section will pop up beneath the rest of the controls on the sidebar.

In the section there are two subsections, one which shows the selected components which form the plot (those you have added previously), and the available components. You can select the probes you want to remove in the **"selected components"** zone, by clicking **"Remove selected components"** the components will be removed from the plot. Inversely, in the **"Available components"** section, you can select the plots you want to add, and by clicking **"Add selected components"** you can add the selected components to the selected plot.

A.1.5 Removing a plot

By left-clicking the plot, a popup appears, you can click **"Remove plot"**, this removes it from the selected plot.

A.2 Sidebar: Probes settings

Now that you have create your outcome diagram, you can modify the probes settings to set the $dMax$ you want and the QTA you desire.

A.2.1 Setting a QTA

You can set a QTA in the **"Set a QTA"** section, there you are presented with the possibility to:

- Select the probe for which you want to set the QTA.
- Set the QTA at the three percentiles (25%, 50%, 75%), the text to the left indicates which percentile is which. You need to set the delay in seconds.
- The minimum amount of successful events you can allow, which is bigger than 75%.

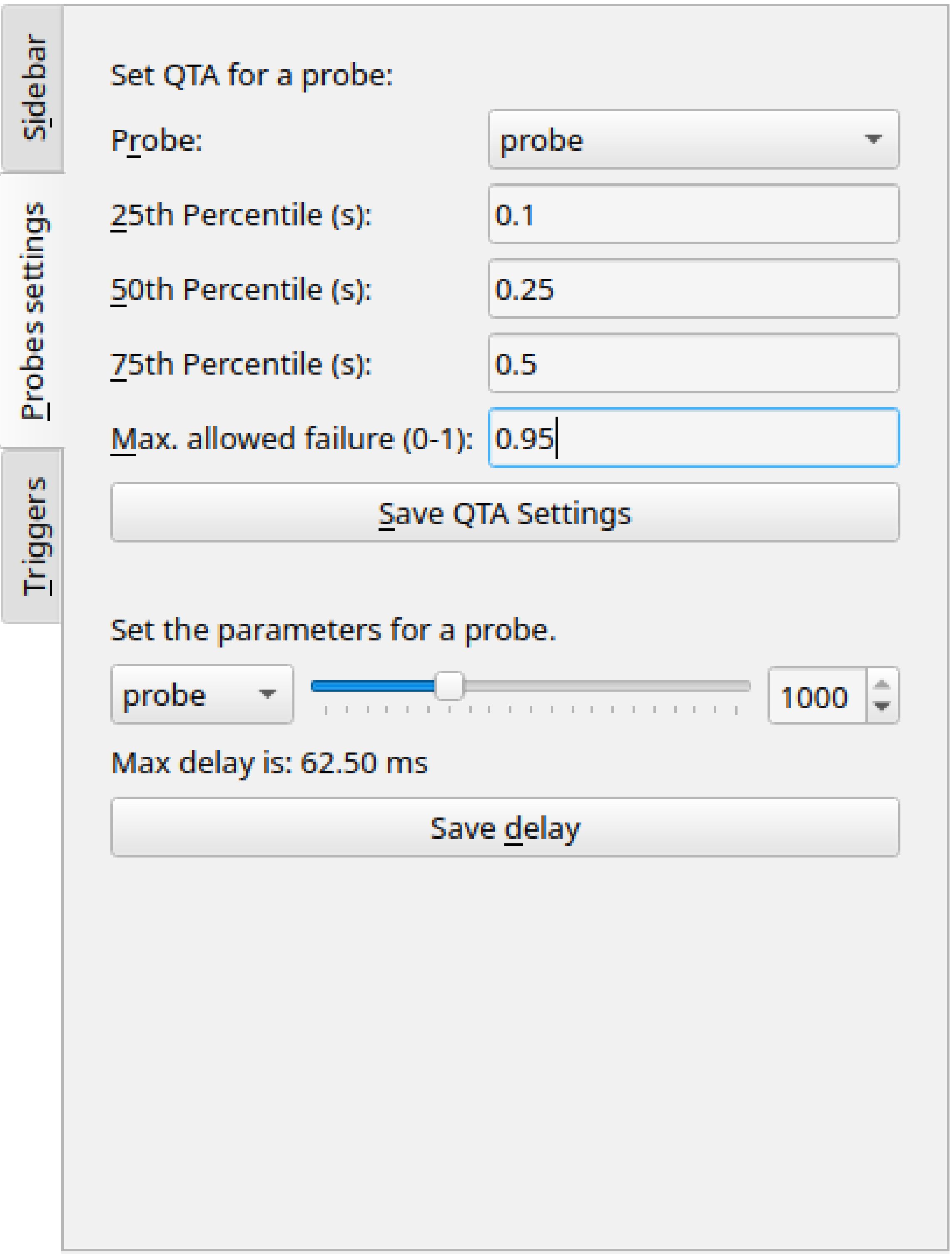
Of course, for the delay of the QTA at three percentiles, the delay at the percentile must be higher or equal than the delay at the previous percentile and higher than 0.

By pressing *"Save QTA settings"* you will save the QTA for the defined probe.

A.2.2 Setting the parameters of a probe

You can set the parameters for a probe in its section. To the left you can select the probe you want to set the parameter for. We provide a slider (which goes from -10 to 10) for the n parameters, to the right of the slider, you can select the number of bins for the probe. The maximum delay calculated will be shown below.

Once you press **"Save delay"**, a message to the erlang wrapper will be sent, which will set the maximum delay you have set in the wrapper.



Set QTA for a probe:

Probe: probe

25th Percentile (s): 0.1

50th Percentile (s): 0.25

75th Percentile (s): 0.5

Max. allowed failure (0-1): 0.95

Set the parameters for a probe.

probe 1000

Max delay is: 62.50 ms

Figure A.1: Probes settings tab. Above: QTA settings. Below: Probe parameters settings.

A.3 Triggers

In the triggers section you can define which triggers to apply for a given probe, once selected, they will be automatically activated.

Once a trigger is triggered, the oscilloscope will keep recording the system for a few seconds. Once stopped, under the "snapshots" section, you can click the snapshots to view them in a separate section, there, you can observe the ΔQs of all the probes before and after the trigger was triggered. You can discard the snapshot by left clicking on it and clicking *"Deleted snapshot"*.

A.4 Instrumenting the Erlang application

A.4.1 Including the wrapper

The Erlang project you need to instrument needs to include the wrapper in its dependencies, to do that, you need to include it in your dependencies.

```
    %your_app.app.src
{application, otel_getting_started, [
    ...
    {applications, [
        kernel,
        stdlib,
        opentelemetry,
        opentelemetry_api,
    opentelemetry_exporter,
    dqsd_otel
    ]},
    ...
    ]}.

    {deps, [
    {opentelemetry, "~> 1.3"},
    {opentelemetry_api, "~> 1.2"},
    {opentelemetry_exporter, "~> 1.0"},
    {dqsd_otel, {git, "https://github.com/fnieri/dqsd_otel.git", {tag,
     ↪  "the_latest_version_on_git"}}}
]}.
```

Once you have the dependencies set up you can begin creating outcome instances for the oscilloscope.

(**Note:** If the project were to change name, you can still find the project in https://github.com/fnieri/).

A.4.2 Starting spans

To start spans you need to call:

```
{ProbeCtx, Pid} = dqsd_otel:start_span(<<"probe">>, #{attributes =>
↪  [{attr, <<"my_attr_5o5s10">>}]}),
```

This will give you the OpenTelemetry context of the probe and the Pid of the process to call upon end. It is left up to you to decide how to carry both in the execution. The function calls OpenTelemetry `?start_span` macro, effectively replacing it.

A.4.3 Ending spans

To end spans you need to call:

```
dqsd_otel:end_span(ProbeCtx, ProbePid)
```

This will end the span on the OpenTelemetry side and end the outcome instance if it hasn't timedout The function calls OpenTelemetry `?end_span` macro, effectively replacing it.

A.4.4 Failing outcome instances

To fail **custom** spans you need to call:

```
dqsd_otel:fail_span(WorkerPid),
```

Contrary to the other methods, this does not end OpenTelemetry spans, it is let up to you to decide how to handle failure in spans.

A.5 Establishing connection to the oscilloscope

WIP

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**