



JaqalTM, the Quantum Assembly Language for QSCOUT

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To Learn More

To learn more about QSCOUT and the JaqalTM language developed for it, please visit qscout.sandia.gov or send an e-mail to qscout@sandia.gov.

Introduction

QSCOUT is the Quantum Scientific Computing Open User Testbed, a trapped-ion quantum computer testbed realized at Sandia National Laboratories on behalf of the Department of Energy's Office of Science and its Advanced Scientific Computing Research (ASCR) program. As an open user testbed, QSCOUT provides the following to its users:

- **Transparency:** Full implementation specifications of the underlying native trapped-ion quantum gates.
- **Extensibility:** Pulse definitions can be programmed to generate custom trapped-ion gates.
- **Schedulability:** Users have full control of sequential and parallel execution of quantum gates.

QSCOUT Hardware 1.0

The first version (1.0) of the QSCOUT hardware realizes a single register of qubits stored in the hyperfine clock states of trapped $^{171}\text{Yb}^+$ ions arranged in a one-dimensional chain. Single and multi-qubit gates are realized by tightly focused laser beams that can address individual ions. The native operations available on this hardware include the following:

- Global preparation and measurement of all qubits in the z basis.
- Parallel single-qubit rotations about any axis in the equatorial plane of the Bloch sphere.
- The Mølmer–Sørensen two-qubit gate between any pair of qubits, in parallel with no other gates.
- Single-qubit Z gates executed virtually by adjusting the reference clocks of individual qubits.

Importantly, QSCOUT 1.0 does not support measurement of a subset of the qubits. Consequently, it also does not support classical feedback. This is because, for ions in a single chain, the resonance fluorescence measurement process destroys the quantum states of all qubits in the ion chain, so that there are no quantum states onto which feedback can be applied. Future versions of the QSCOUT hardware will support feedback.

QSCOUT 1.0 uses ***Just Another Quantum Assembly Language (Jaqal)*** (described [below](#)) to specify quantum programs executed on the testbed. On QSCOUT 1.0, every quantum computation starts with preparation of the quantum state of the entire qubit register in the z basis. Then it executes a sequence of parallel and sequential single and two-qubit gates. After this, it executes a simultaneous measurement of all qubits in the z basis, returning the result as a binary string. This sequence of prepare-all/do-gates/measurement-all can be repeated multiple times in a Jaqal program, if desired. However, any adaptive program that uses the results of one such sequence to issue a subsequent sequence must be done with metaprogramming, because Jaqal does not currently support feedback. Once the QSCOUT platform supports classical feedback, Jaqal will be extended to support it as well.

Gate Pulse File

The laser pulses that implement built-in or custom trapped-ion gates are defined in a ***Gate Pulse File (GPF)***. Eventually, users will be able to write their own GPF files, but that capability will not be available in our initial software release. However, users will be free to specify composite gates by defining them as sub-circuit [macros](#). Additionally, custom native gates can be added in collaboration with Sandia scientists by specifying the pulse sequences that have to be applied to the trapped ion qubits to realize the gate.

We have provided a GPF file for the built-in gates on the QSCOUT 1.0 platform. This file is not intended to be modified by users, so we are not specifying its contents here. However, a full specification of the built-in gates will be available to users of the QSCOUT 1.0 platform. This GPF file contains pulse-level gate definitions for the QSCOUT 1.0 built-in gates listed below. All angle arguments in this list are in the units of radians, with 40 bits of precision. The chirality of rotations is determined using the right-hand rule.

- `prepare_all`
Prepares all qubits in the quantum register in the $|0\rangle$ state in the z basis.
- `R <qubit> <axis angle> <rotation angle>`
Counter-clockwise rotation around an axis in the equatorial plane of the Bloch sphere defined by `<axis-angle>`, measured counter-clockwise from the x axis, by the angle defined by `<rotation angle>`.
- `Rx <qubit> <rotation angle>`
Counter-clockwise rotation around the x axis, by the angle defined by `<rotation angle>`.
- `Ry <qubit> <rotation angle>`
Counter-clockwise rotation around the y axis, by the angle defined by `<rotation angle>`.
- `Rz <qubit> <angle>`
Counter-clockwise rotation around the z axis, by the angle defined by `<rotation angle>`.
- `Px <qubit>`
Counter-clockwise rotation around the x axis, by π . (Pauli X gate.)
- `Py <qubit>`
Counter-clockwise rotation around the y axis, by π . (Pauli Y gate.)
- `Pz <qubit>`
Counter-clockwise rotation around the z axis, by π . (Pauli Z gate.)

- **Sx <qubit>**
Counter-clockwise rotation around the x axis, by $\pi/2$. (\sqrt{X} gate.)
- **Sy <qubit>**
Counter-clockwise rotation around the y axis, by $\pi/2$. (\sqrt{Y} gate.)
- **Sz <qubit>**
Counter-clockwise rotation around the z axis, by $\pi/2$. (\sqrt{Z} gate.)
- **Sxd <qubit>**
Clockwise rotation around the x axis, by $\pi/2$. (\sqrt{X}^\dagger gate.)
- **Syd <qubit>**
Clockwise rotation around the y axis, by $\pi/2$. (\sqrt{Y}^\dagger gate.)
- **Szd <qubit>**
Clockwise rotation around the z axis, by $\pi/2$. (\sqrt{Z}^\dagger gate.)
- **MS <qubit> <qubit> <axis angle> <rotation angle>**
The general two-qubit Mølmer-Sørensen gate. (If we let θ represent <rotation angle> and φ represent <axis angle>, then the gate is

$$\exp\left(-i\left(\frac{\theta}{2}\right)(\cos\varphi X + \sin\varphi Y)^{\otimes 2}\right).$$

- **Sxx <qubit> <qubit>**
The XX-type two-qubit Mølmer-Sørensen gate:

$$\exp\left(-i\left(\frac{\pi}{2}\right)X \otimes X\right).$$

- **measure_all**
Measures all qubits of the quantum register in the z basis. After measurement, ions will be outside the qubit space. Therefore, the qubits have to be prepared again before any other gates can be applied.

The gate pulse definitions also include idle gates with the same duration as the single- and two-qubit gates. These have a prefix of **I_**. For example an idle gate of the same duration as a **Px** can be obtained by **I_Px <qubit>**. It is important to note that it is not necessary to explicitly insert idle on idling qubits in a parallel block. Explicit idle gates are meant to be used for performance testing and evaluation.

Jaqal Quantum Assembly Language

The open nature of the QSCOUT testbed requires a flexible **Quantum Assembly Language (QASM)** that empowers QSCOUT users to extend the set of native gates and fully control the execution of the quantum program on the QSCOUT testbed. Due to the proliferation of such languages in this fledgling field, ours is named **Just Another Quantum Assembly Language**, or **Jaqal**.

To realize our objectives, the Jaqal QASM language fulfills the following requirements:

- Jaqal fully specifies the allocation of qubits within the quantum register, which *cannot* be altered during execution.
- Jaqal requires the scheduling of sequential and parallel gate sequencing to be fully and explicitly specified.
- Jaqal can execute any native (built-in or custom) gate specified in any GPF file it references.

While Jaqal is built upon a lower-level pulse definition in GPF files, it is the lowest-level QASM programming language exposed to users in QSCOUT. We anticipate that users will develop their own higher-level programming languages that compile down to Jaqal. We plan to release Jaqal-branded metaprogramming tools after user-driven innovation at this meta-programming level settles down.

Jaqal Syntax

A Jaqal file consists of gates and metadata making those gates easier to read and write. The gates that are run on the machine can be deterministically computed by inspection of the source text. This implies that there are no conditional statements at this level. This section will describe the workings of each statement type.

Whitespace is largely unimportant except as a separator between statements and their elements. If it is desirable to put two statements on the same line, a ';' separator may be used. In a parallel block, the pipe('|') must be used instead of the ';'. Like the semicolon, however, the pipe is unnecessary to delimit statements on different lines. Both Windows and Linux newline styles will be accepted.

Identifiers

Gate names and qubit names have the same character restrictions. Similar to most programming languages, they may contain, but not start with, numerals. They are case sensitive and may contain any non-accented Latin character plus the underscore. Identifiers cannot be any of the keywords of the language.

Comments

C/C++ style comments are allowed and treated as whitespace. A comment starting with '//' runs to the end of the current line, while a comment with '/*' runs until a '*' is encountered. These comments do not nest, which is the same behavior as C/C++.

Header Statements

A properly formatted Jaqal file comprises a header and body section. All header statements must precede all body statements. The order of header statements is otherwise arbitrary except that all objects must be defined before their first use.

Register Statement

A register statement serves to declare the user's intention to use a certain number of qubits, referred to in the file with a given name. If the machine cannot supply this number of qubits then the entire program is rejected immediately.

The following line declares a register named `q` which holds 7 qubits.

```
register q[7]
```

Map Statement

While it is sufficient to refer to qubits by their offset in a single register, it is more convenient to assign names to individual qubits. The map statement effectively provides an alias to a qubit or array of qubits under a different name. The following lines declare the single qubit `q[0]` to have the name `ancilla` and the array `qubits` to be an alias for `q`. Array indices start with 0.

```
register q[3]
map ancilla q[0]
map qubits q
```


The map statement will also support Python-style slicing. In this case, the map statement always declares an array alias. In the following line we relabel every other qubit to be an ancilla qubit, starting with index 1.

```
register q[7]
map ancilla q[1:7:2]
```

After this instruction, `ancilla[0]` corresponds to `q[1]`; `ancilla[1]` and `ancilla[2]` correspond to `q[3]` and `q[5]`, respectively.

Let Statement

We allow identifiers to replace integers or floating point numbers for convenience. There are no restrictions on capitalization. An integer defined in this way may be used in any context where an integer literal is valid and a floating point may similarly be used in any context where a floating point literal is valid. Note that the values are constant, once defined.

Example:

```
let total_count 4
let rotations 1.5
```

Body Statements

Gate Statement

Gates are listed, one per statement, meaning it is terminated either by a newline or a separator. The first element of the statement is the gate name followed by the gate's arguments which are whitespace-separated numbers or qubits. Elements of quantum registers, mapped aliases, and local variables (see section on [macros](#)) may be freely interchanged as qubit arguments to each gate. The names of the gates are fixed but determined in the Gate Pulse File, except for macros. The number of arguments ("arity") must match the expected number. The following is an example of what a 2-qubit gate may look like.

```
register q[3]
map ancilla q[1]
Sxx q[0] ancilla
```

The invocation of a macro is treated as completely equivalent to a gate statement.

Gate Block

Multiple gates and/or macro invocations may be combined into a single block. This is similar, but not completely identical, to how C or related languages handle statement blocks. Macro definitions and header statements are not allowed in gate blocks. Additionally, statements such as macro definitions or loops expect a gate block syntactically and are not satisfied with a single gate, unlike C.

Two different gate blocks exist: sequential and parallel. Sequential gate blocks use the standard C-style '{ }' brackets while parallel blocks use angled '< >' brackets, similar to C++ templates. This choice was made to not conflict with '[']' brackets, which are used in arrays, and to reserve '()' for possible future use. In a sequential block, each statement, macro, or gate block waits for the previous to finish before executing. In a parallel gate block,

all operations are executed at the same time. It is an error to request parallel operations that the machine is incapable of performing, however it is not syntactically possible to forbid these as they are determined by hardware constraints which may change with time.

Looping statements are allowed inside sequential blocks, but not inside parallel blocks. Blocks may be arbitrarily nested so long as the hardware can support the resulting sequence of operations. Blocks may not be nested directly within other blocks of the same type.

The following statement declares a parallel block with two gates.

```
< Sx q[0] | Sy q[1] >
```

This does the same but on different lines.

```
<
  Sx q[0]
  Sy q[1]
>
```

Here is a parallel block nested inside a sequential one.

```
{
  Sxx q[0] q[1]
  < Sx q[0] | Sy q[1] >
}
```

And sequential blocks may be nested inside parallel blocks.

```
<
  Sx q[0]
  { Sx q[1] ; Sy q[1] }
>
```

Timing within a parallel block If two gates are in a parallel block but have different durations (e.g., two single-qubit gates of different length), the default behavior is to *start* each gate within the parallel block simultaneously. The shorter gate(s) will then be padded with idles until the end of the gate block. For example, the command

```
<
  Rx q[1] 0.1
  Sx q[2]
>
```

results in the Rx gate on q[1] with angle 0.1 radians and Sx gate on q[2] both starting at the same time; the Rx gate will finish first and q[1] will idle while the Sx gate finishes. Once the Jaqal gate set becomes user-extensible, users may define their own scheduling within parallel blocks (e.g., so that gates all *finish* at the same time instead).

Macro Statement

A macro can be used to treat a sequence of gates as a single gate. Gates inside a macro can access the same qubit registers and mapped aliases at the global level as all other gates, and additionally have zero or more arguments which are visible. Arguments allow the same macro to be applied on different combinations of physical qubits, much like a function in a classical programming language.

A macro may use other macros that have already been declared. A macro declaration is complete at the *end* of its code block. This implies that recursion is impossible. It also implies that macros can only reference other macros created earlier in the file. Due to the lack of conditional statements, recursion always creates an infinite loop and is therefore never desirable.

A macro is declared using the `macro` keyword, followed by the name of the macro, zero or more arguments, and a code block. Unlike C, a macro must use a code block, even if it only has a single statement.

The following example declares a macro.

```
macro foo a b {  
    Sx a  
    Sxx a q[0]  
    Sxx b q[0]  
}
```

To simplify parsing, a line break is not allowed before the initial '{', unlike C. However, statements may be placed on the same line following the '{'.

Loop Statement

A gate block may be executed for a fixed number of repetitions using the loop statement. The loop statement is intentionally restricted to running for a fixed number of iterations. This ensures it is easy to deterministically evaluate the runtime of a program. Consequently, it is impossible to write a program which will not terminate.

The following loop executes a sequence of statements seven times.

```
loop 7 {  
    Sx q[0]  
    Sz q[1]  
    Sxx q[0] q[1]  
}
```

The same rules apply as in macro definitions: '{' must appear on the same line as `loop`, but other statements may follow on the same line.

Loops may appear in sequential gate blocks, but not in parallel gate blocks.

Extensibility

As Jaqal and the QSCOUT project more broadly have extensibility as stated goals, it is important to clarify what is meant by this term. Primarily, Jaqal offers extensibility in the gates that can be performed. This will occur through the gate pulse file and the use of macros to define composite gates that can be used in all contexts a native gate can. Jaqal will be incrementally improved as new hardware capabilities come online and real world use

identifies areas for enhancement. The language itself, however, is not intended to have many forms of user-created extensibility as a software developer might envision the term. Features we do not intend to support include, but are not limited to, pragma statements, user-defined syntax, and a foreign function interface (i.e. using custom C or Verilog code in a Jaqal file).

Examples

Bell state preparation

This example prepares a Bell state using the classic Hadamard and controlled X circuit, then measures it in the computational basis. Up to the limits of gate fidelity, the measurements of the two qubits should always match.

```
macro hadamard target { // A Hadamard gate can be implemented as
    Sy target           // a pi/2 rotation around Y
    Px target           // followed by a pi rotation around X.
}

macro cnot control target { // CNOT implementation from Maslov (2017)
    Sy control           //
    Sxx control target
    <Sxd control | Sxd target> // we can perform these in parallel
    Syd control
}

register q[2]

prepare_all           // Prepare each qubit in the computational basis.
hadamard q[0]
cnot q[1] q[0]
measure_all           // Measure each qubit and read out the results.
```

However, there's a more efficient way of preparing a Bell state that takes full advantage of the native Mølmer-Sørensen interaction of the architecture, rather than using it to replicate a controlled-X gate. The following snippet of code repeats that interaction 1024 times, measuring and resetting the ions after each time. All 1024 measurement results will be reported to the user.

```
register q[2]

loop 1024 {
    prepare_all
    Sxx q[0] q[1]
    measure_all
}
```

Single-Qubit Gate Set Tomography

```
register q[1]

// Fiducials
```



```

macro F0 qubit { I_Sx qubit }
macro F1 qubit { Sx qubit }
macro F2 qubit { Sy qubit }
macro F3 qubit { Sx qubit; Sy qubit}
macro F4 qubit { Sx qubit; Sx qubit; Sx qubit }
macro F5 qubit { Sy qubit; Sy qubit; Sy qubit }

// Germs
macro G0 qubit { Sx qubit }
macro G1 qubit { Sy qubit }
macro G2 qubit { I_Sx qubit }
macro G3 qubit { Sx qubit; Sy qubit }
macro G4 qubit { Sx qubit; Sy qubit; I_Sx qubit }
macro G5 qubit { Sx qubit; I_Sx qubit; Sy qubit }
macro G6 qubit { Sx qubit; I_Sx qubit; I_Sx qubit }
macro G7 qubit { Sy qubit; I_Sx qubit; I_Sx qubit }
macro G8 qubit { Sx qubit; Sx qubit; I_Sx qubit; Sy qubit }
macro G9 qubit { Sx qubit; Sy qubit; Sy qubit; I_Sx qubit }
macro G10 qubit { Sx qubit; Sx qubit; Sy qubit; Sx qubit; Sy qubit; Sy qubit }

// Length 1
prepare_all
F0 q[0]
measure_all

prepare_all
F1 q[0]
measure_all

prepare_all
F2 q[0]
measure_all

prepare_all
F3 q[0]
measure_all

prepare_all
F4 q[0]
measure_all

prepare_all
F5 q[0]
measure_all

prepare_all
F1 q[0]; F1 q[0]
measure_all

prepare_all
F1 q[0]; F2 q[0]
measure_all

```

```
// and many more
// Repeated germs can be realized with the loop

prepare_all
F1 q[0]
loop 8 { G1 q[0] }
F1 q[0]
measure_all
```

Data Output Format

When successfully executed, a single Jaqal file will generate a single ASCII text file (Linux line endings) in the following way:

1. Each call of `measure_all` at runtime will add a new line of data to the output file. (If `measure_all` occurs within a loop (or nested loops), then multiple lines of data will be written to the output file, one for each call of `measure_all` during execution.)
2. Each line of data written to file will be a single bitstring, equal in length to the positive integer passed to register at the start of the program.
3. Each bitstring will be written in least-significant bit order (little endian).

For example, consider the program:

```
register q[2]

loop 2 {
    prepare_all
    Px q[0]
    measure_all
}

loop 2 {
    prepare_all
    Px q[1]
    measure_all
}
```

Assuming perfect execution, the output file would read as:

```
10
10
01
01
```

While this output format will be “human-readable”, it may nevertheless be unwieldy to work with directly. Therefore, a Python-based parser will be written to aid users in manipulating output data.

Possible Future Capabilities

Jaqal is still under development, and will gain new features as the QSCOUT hardware advances. While the precise feature set of future versions of Jaqal is still undetermined, we discuss some features that may be added, and in some cases identify workarounds for the current lack of those features.

Subset Measurement

Currently, the measurement operation of the QSCOUT hardware acts on all ions in the trap, destroying their quantum state and taking them out of the computational subspace. Future versions of the QSCOUT hardware will allow for the isolation and measurement of a subset of qubits with a command of the form `measure_subset <qubit>`. Similarly, a `prepare_subset <qubit> ...` operation will allow the reuse of measured qubits without destroying the quantum state of the remainder. These would be implemented in a Gate Pulse File, and not require a change to the Jaqal language.

Measurement Feedback

The QSCOUT hardware does not currently support using measurement outcomes to conditionally execute future gates. We expect this capability will be added in a future version of the QSCOUT hardware, and Jaqal programs will be able to use that capability once it exists. We have chosen to delay adding the syntax for measurement feedback to Jaqal until that time, in order to allow us the flexibility to choose a syntax that best allows users to take advantage of the actual capabilities of our hardware, once those are known.

Classical Computation

Jaqal does not currently support any form of classical computation. We understand that this is a limitation, and expect future versions of Jaqal to do so. There are two relevant forms of classical computation that we are considering for Jaqal.

Compile-Time Classical Computation

Performing classical computations at compile-time, before the program is sent to the quantum computer, can vastly increase the expressiveness of the language. For example, consider the following experiment, *which is not currently legal Jaqal code*:

```
register q[1]

let pi 3.1415926536

loop 100 {
  prepare_all
  Ry q[0] pi/32
  measure_all
  prepare_all
  Ry q[0] pi/16
  measure_all
  prepare_all
  Ry q[0] 3*pi/32
}
```

```

    measure_all
    prepare_all
    Ry q[0] pi/8
    measure_all
}

```

Currently, Jaqal does not support inline parameter calculations like the above. The recommended workaround is to define additional constants as needed:

```

register q[1]

let pi_32    0.09817477042
let pi_16    0.1963495408
let pi_3_32  0.2945243113
let pi_8     0.3926990817

loop 100 {
    prepare_all
    Ry q[0] pi_32
    measure_all
    prepare_all
    Ry q[0] pi_16
    measure_all
    prepare_all
    Ry q[0] pi_3_32
    measure_all
    prepare_all
    Ry q[0] pi_8
    measure_all
}

```

Another example of a case where compile-time classical computation could be useful is in macro definition. For example, if you wished to define a macro for a controlled z rotation in terms of a (previously-defined) CNOT macro:

```

...
macro CNOT control target { ... }

macro CRz control target angle {
    Rz target angle/2
    CNOT control target
    Rz target -angle/2
    CNOT control target
}
...

```

Again, the above example *is not currently legal Jaqal*. We recommend, in such cases, that you manually unroll macros as needed, then define additional constants as above. That is, rather than using the above macro:

```

...
let phi 0.7853981634;

```



```
...
CRz q[0] q[1] phi;
...
```

You should instead call the gates the macro is made up of, substituting the results of the appropriate calculations yourself:

```
...
let phi 0.7853981634;
let phi_2 0.3926990817;
let phi_m_2 -0.3926990817;
...
Rz q[1] phi_2; CNOT q[0] q[1]; Rz q[1] phi_m_2; RNOT q[0] q[1];
...
```

We recognize that this “manual compilation” is a significant inconvenience for writing readable and expressive code in Jaqal. We expect to include compile-time classical computation in a relatively early update to Jaqal, likely even before measurement feedback is available. Fortunately, metaprogramming (automated code generation) significantly eases the burden of the lack of classical computation features, and we highly recommend it to users of Jaqal.

Run-Time Classical Computation

Users may also wish to do classical computation while a Jaqal program is running, based on the results of measurements. For example, in hybrid variational algorithms, a classical optimizer may use measurement results from one circuit to choose rotation angles used in the next circuit. In error-correction experiments, a decoder may need to compute which gates are necessary to restore a state based on the results of stabilizer measurements. Adaptive tomography protocols may need to perform statistical analyses on measurement results to determine which measurements will give the most information. As can be seen from the above examples, run-time classical computation is useful only when measurement feedback is possible. Accordingly, we will consider this feature after we have added support for measurement feedback. However, use cases like adaptive tomography and variational algorithms can be implemented via metaprogramming techniques. After running a Jaqal file on the QSCOUT hardware, a metaprogram can parse the [measurement results](#), then use that information to generate a new Jaqal file to run.

Randomness

Executing quantum programs with gates chosen via classical randomness is desirable for a variety of reasons. Applications of randomized quantum programs include hardware benchmarking, error mitigation, and some quantum simulation algorithms. Jaqal does not currently have built-in support for randomization, although it may in the future, likely in combination with support for run-time classical computation. Our currently recommended workaround is to pre-compute any randomized elements of the algorithm, automatically generating Jaqal code to execute the random circuit selected. For example, the following program isn't currently possible, as there's no means of generating a random angle in Jaqal directly:

```
register q[1]

loop 100 {
  prepare_all
```

```

    // Do an X rotation on q[0] by a random angle between 0 and 2*pi.
    measure_all
}

```

However, the same effect can be obtained by a metaprogram (written in Python, for the sake of example) that generates a Jaqal program:

```

from random import uniform
from math import pi
with open("randomness_example.jql", "w") as f:
    f.write("register q[1]\n\n")
    for idx in range(100):
        angle = uniform(0.0, 2.0 * pi)
        f.write("prepare_all\n")
        f.write("Rx q[0] %f\n" % angle)
        f.write("measure_all\n\n")

```

While the generated Jaqal program is much larger than one that could be written in a potential future version of Jaqal that supported randomized execution, the metaprogram that generates it is quite compact.

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