A #QuantumComputerArchitecture Tweetstorm

Rodney Van Meter

Keio University

Quantum computer architecture, as a field, can trace its roots to the mid-1990s, essentially contemporaneous with the initial surge of interest in quantum computing. In the early 2000s, researchers with formal education in classical computer architecture joined the field, and progress has been steady. This article reviews some of the key eras of the last quarter-century, organized into the four themes of architecture-aware compilation, architectures for large-scale systems (including quantum error correction), classical control systems (including input/output, or I/O), and "NISQy business" (in Joe Fitzsimons' phrase).

Introduction

In August 2019, an article by Sabine Hossenfelder that appeared in *The Guardian* [37] resulted in a conversation (known as a "thread") on Twitter with the article's author. The thread covered the state of the field of quantum computer architecture and the extent to which the quantum computing community is preparing to build large-scale systems once the milestone of "quantum supremacy" has been achieved. Earl Campbell wrote a reasoned response [10], after which I wound up writing a sequence of 186 tweets, called a "tweetstorm", on the history of the field of quantum computer architecture. At the urging of several people, in this article I am compiling that tweetstorm, in almost unedited form, as it would appear to a reader of the thread.

I conceived of the overall structure of the thread quickly, though I did not anticipate the full scope until the project was underway. The tweets were composed and posted in small batches over a period of about 100 hours; they are very much in the form of Twitter's interactive conversation. Upon rereading the thread while composing this article, I find that there is very little that I would change even given the chance, with two possible exceptions.

When I give talks on quantum computer architecture, I begin by defining architecture, and emphasize importance of workload in defining a computer system.

One definition of *architecture* that I like to quote comes from the Oxford New English Dictionary:

> **2** the complex or carefully designed structure of something: *the chemical architecture of the human brain.*
> · the conceptual structure and logical organization of a computer or computer-based system: *a client/server architecture.*

Architecture, particularly as used in the field of computer architecture, refers to the division of a system into subsystems, defining the roles of each subsystem and the interfaces between them.

Classical computers are not, and have never been, designed and built without reference to their intended use. The projected *workload* of the computer is used in the construction of metrics that can be used to make objective design decisions. Such metrics may be absolute number of computations achieved per second on a specified set of programs, known as *benchmarks*, or may be computations per second per dollar of system cost, or increasingly computations per second per watt of power consumed. Quantum computers likewise will built with a focus on specific applications.

It is worth noting that this tweetstorm focused

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only on gate-based quantum computation; quantum annealers [31, 43] would be a separate topic. Although some consider measurement-based quantum computation (MBQC) and quantum walks to be separate, their implementations and algorithms built on top of them are intimately connected to gate-based systems, so here we will consider them to be implicitly incorporated.

Notes on reading this article: Each individual tweet is included with no edits except as noted below. Only my own tweets are included here; a handful of other contributors offered additional comments during and after the completion of this tweetstorm, and are worth reading. This article is intended to be read in electronic form, and includes active links to all of the articles mentioned. Any individual tweet can be accessed on Twitter by clicking on the timestamp.

1 Thread 1: Architecture-Aware Compilation

The HHL algorithm referred to in tweet 1.10 is [33].

Tweet 1.1:


Rod Van Meter @rdviii

in reply to tweet by @skdh

@skdh @earltcampbell You are asking for several hours of my time.
Okay, I really had other plans for this morning, including prepping to talk to a potential funding agency this afternoon, but here goes...
Let's talk #QuantumComputer architecture, broadly.

↻57 ♡209 Tue Aug 06 02:00:53 +0000 2019

Tweet 1.2:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Let's divide the scalability problem into four areas:
1. architecture-aware compilation of realistic algorithms, including
resource analysis and error correction (QEC)
2. architecture of large-scale quantum computers, including QEC
3. classical control systems
4. NISQy business

↻12 ♡55 Tue Aug 06 02:01:30 +0000 2019

Tweet 1.3:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (to borrow Joe Fitzsimons' fantastic phrase)

↻0 ♡13 Tue Aug 06 02:01:38 +0000 2019

Tweet 1.4:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (In the interest of some amount of brevity, I'm going to name only one author for most papers; my apologies to those left out. I'll also stick to arXiv and open access links where I can.)

↻0 ♡13 Tue Aug 06 02:01:59 +0000 2019

Tweet 1.5:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Also, some of this we have covered here on Twitter in the last couple of years, but sometimes it's easier to recreate than find the links.)

↻0 ♡10 Tue Aug 06 02:02:24 +0000 2019

Tweet 1.6:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell 1. IMO, the first compilations of quantum algorithms (done by hand, as most of the papers cited here are) were VBE and BCDP, both focusing on Shor, but with little architecture focus (more in BCDP).
arxiv.org/abs/quant-ph/9...
arxiv.org/abs/quant-ph/9...

↻0 ♡17 Tue Aug 06 02:02:51 +0000 2019

Tweet 1.7:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Nearly a decade later, Simon Devitt, Austin Fowler and I came along, with more of a focus on architecture awareness, but still without QEC.
arxiv.org/abs/quant-ph/0...
arxiv.org/abs/quant-ph/0...

arxiv.org/abs/quant-ph/0...
↻1 ♡16 Tue Aug 06 02:06:19 +0000 2019

Tweet 1.8:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell My collaborator Byung-Soo Choi, yet another person with a classical architecture background, focused on architecture-aware circuits.
arxiv.org/abs/0809.4317
arxiv.org/abs/1008.5093
↻0 ♡14 Tue Aug 06 02:06:41 +0000 2019

Tweet 1.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell A few years later, Cody Jones and James Whitfield worked on quantum chemistry, this time taking into consideration some aspects of QEC.
arxiv.org/abs/1204.0567
↻0 ♡15 Tue Aug 06 02:07:00 +0000 2019

Tweet 1.10:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Around that same time, the IARPA program was under way and HHL was all the rage, but Clader, Scherer, and others found shocking consumption of resources for the problems IARPA asked for.
arxiv.org/abs/1301.2340
doi.org/10.1007/s11128...
↻0 ♡14 Tue Aug 06 02:07:21 +0000 2019

Tweet 1.11:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This was the era that brought Margaret Martonosi into the community, and saw the development of some of the first nearly-practical programming languages, such as Scaffold.
doi.org/10.1016/j.parc...
↻0 ♡13 Tue Aug 06 02:08:15 +0000 2019

Tweet 1.12:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Quipper, from Green, Selinger and others, and used by Siddiqui and Islam, is another.
arxiv.org/abs/1304.3390
arxiv.org/abs/1406.4481
↻1 ♡11 Tue Aug 06 02:08:39 +0000 2019

Tweet 1.13:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell They, and Jon Dowling and Ken Brown, can probably answer additional questions about their findings on resource consumption for various algorithms.
↻0 ♡12 Tue Aug 06 02:09:03 +0000 2019

Tweet 1.14:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Krysta Svore and Andrew Cross, working with Ike Chuang, published an influential paper on software architectures in the early days.
ieeexplore.ieee.org/abstract/docum...
↻1 ♡17 Tue Aug 06 02:09:21 +0000 2019

Tweet 1.15:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell After Krysta joined Microsoft, she initiated a team with Dave Wecker, Matthias Troyer, Nathan Wiebe, Martin Roetteler and Alex Bocharov and worked on programming languages and resource counts for quantum chemistry, elliptic curve, optimization algorithms, etc.,
↻1 ♡12 Tue Aug 06 02:09:57 +0000 2019

Tweet 1.16:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell some including architecture awareness and attention to errors.
arxiv.org/abs/1402.4467
arxiv.org/abs/1803.00652
arxiv.org/abs/1312.1695
arxiv.org/abs/1401.2142
arxiv.org/abs/1706.06752
↻1 ♡12 Tue Aug 06 02:10:12 +0000 2019

Tweet 1.17:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This era also saw some advances in arithmetic, useful for Shor's algorithm but also much more. I like the Pavlidis paper, despite not being a big fan of the QFT-based adder.
arxiv.org/abs/1207.0511

0 ♡12 Tue Aug 06 02:10:33 +0000 2019

Tweet 1.18:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I assume you're aware of the Quantum Algorithm Zoo (quantumalgorithmzoo.org).
I've been saying for years that one of the key things we in the community need to be focusing on is establishing *concrete* use cases for those algorithms,

2 ♡20 Tue Aug 06 02:11:09 +0000 2019

Tweet 1.19:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell including resource counts for both small-machine
demonstrations and desirable large-machine implementations, including error analysis. That is really starting to happen now.

0 ♡13 Tue Aug 06 02:11:31 +0000 2019

Tweet 1.20:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Finally, let me close with another of mine. Horsman and I wrote about the top-to-bottom problem in CACM.
m-cacm.acm.org/magazines/2013...
The SOM is hard to find, but includes 60 more references, many focused on the IARPA-driven problem set:
delivery.acm.org/10.1145/250000...

1 ♡14 Tue Aug 06 02:11:51 +0000 2019

Tweet 1.21:

 Rod Van Meter @rdviii

in reply to tweet by @skdh

@skdh @earltcampbell Direct link must not work properly. Go to
dl.acm.org/citation.cfm?i...
and click on "Source materials", and the SOM is on that page.

0 ♡1 Tue Aug 06 03:59:34 +0000 2019

Tweet 1.22:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell If you get the impression I'm simply bombarding you with volume, rather than a few superhero papers, what I'm trying to convey is that building useful systems is an end-to-end problem, and that *hundreds*, perhaps thousands, of researchers are all pulling in the same
direction,

0 ♡21 Tue Aug 06 02:12:34 +0000 2019

Tweet 1.23:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell trying to solve these problems.
We had almost fifty researchers at the Dagstuhl seminar focused on quantum programming languages last September, organized by Peter, Martin and Michele
Mosca, and that was basically only one representative per research group.

0 ♡10 Tue Aug 06 02:13:20 +0000 2019

Tweet 1.24:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell More than enough for now. And that's just topic one of four I listed above. If you're waiting in the wings to see if I brought up you, or your favorite paper, feel free to chime in, though the odds are good I have that planned for the next segment!
/end (temporary)

0 ♡12 Tue Aug 06 02:13:59 +0000 2019

2 Thread 2: Architecture of Large-Scale Quantum Computers

The "first buildable quantum architecture" referred in tweet 2.3 is [52]. In tweet 2.24, I neglected to mention the name of Muhammad Ahsan, the first author of the paper [1]. The first author of [50] is Bjoern Lekitsch. The first author of [76] is Susanne Richer. The paper discussed in the tweet thread referenced in tweet 2.41 is [27], by Craig Gidney.

Tweet 2.1:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (I apparently branched this once above, which wasn't my intention. I'll try to keep it linear from here.)

0 ♡ 5 Tue Aug 06 12:32:50 +0000 2019

Tweet 2.2:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Okay, let's do this.
Let's talk #QuantumComputer architecture.
Earlier, we discussed the work of the hundreds of researchers working on quantum programming tools and on figuring out the resource requirements of algorithms.
2. Now let's do large-scale architectures.

0 ♡ 13 Tue Aug 06 12:33:15 +0000 2019

Tweet 2.3:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I'm assuming you're familiar with Seth Lloyd's "first buildable quantum architecture", and the basic ideas of solid-state(superconducting, quantum dot), ion trap, all-optical, and optical hybrid (esp. NV diamond).

0 ♡ 9 Tue Aug 06 12:33:35 +0000 2019

Tweet 2.4:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell If not, go read Thaddeus Ladd et al.'s "Quantum computing".
arxiv.org/abs/1009.2267

0 ♡ 11 Tue Aug 06 12:33:59 +0000 2019

Tweet 2.5:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell What we're after here is not few-qubit systems, but designs for *big* machines, capable of running big algorithms with full error correction and scaling to thousands of logical qubits.

0 ♡ 10 Tue Aug 06 12:34:14 +0000 2019

Tweet 2.6:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This doesn't necessarily mean I think this is the _only_ path to _useful_ quantum computers, but it's a route we'll have to follow eventually.

0 ♡ 9 Tue Aug 06 12:34:40 +0000 2019

Tweet 2.7:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The first papers with input from computer architects were by a group centered around Ike Chuang, featuring Fred Chong, Mark Oskin, and John "Kubi" Kubiatowicz.
dl.acm.org/citation.cfm?i...
ieeexplore.ieee.org/abstract/docum...

0 ♡ 10 Tue Aug 06 12:35:04 +0000 2019

Tweet 2.8:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This is 2002-3, just before Simon, Austin and I arrived on the scene, as discussed earlier.

0 ♡ 9 Tue Aug 06 12:35:21 +0000 2019

Tweet 2.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Dean Copsey, Setso Metodi (Tzvetan Metodiev), Darshan Thaker, Andrew Cross, Nemanja Isailovic, Mark Whitney started contributing around this time, too.
arxiv.org/abs/quant-ph/0...
arxiv.org/abs/quant-ph/0...

0 ♡ 8 Tue Aug 06 12:35:42 +0000 2019

Tweet 2.10:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Dean's paper on the costs of moving data around inside big machines led the way. "This is an important paper," I wrote in my notes.
people.cs.uchicago.edu/ ftchong/paper...

0 8 Tue Aug 06 12:36:00 +0000 2019

Tweet 2.11:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Mark and I wrote a survey on the architectural implications of technologies, based on a chapter from my Ph.D. thesis.
dl.acm.org/citation.cfm?i...

0 9 Tue Aug 06 12:36:18 +0000 2019

Tweet 2.12:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The architectural direction I went, which I still maintain is the right one, is quantum "multicomputers", with the name borrowed from classical distributed-memory computers. My undergrad adviser, Chuck Seitz, coined the term, I believe.

1 13 Tue Aug 06 12:39:50 +0000 2019

Tweet 2.13:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I can't say the term has fully caught on, but a number of people had similar ideas.

0 7 Tue Aug 06 12:40:04 +0000 2019

Tweet 2.14:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell My most important paper on multicomputer architecture was at ISCA, the premiere computer architecture conference, same time as a couple of other papers. I later expanded it to a JETC paper.
arxiv.org/abs/quant-ph/0...
iscaconf.org/isca2006/

1 9 Tue Aug 06 12:40:28 +0000 2019

Tweet 2.15:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell My thesis tried to address all of what I considered *architectural* issues, independent of technology.
arxiv.org/abs/quant-ph/0...

0 9 Tue Aug 06 12:40:44 +0000 2019

Tweet 2.16:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Other papers I would classify as multicomputer are Daniel Oi's and Liang Jiang's.
arxiv.org/abs/quant-ph/0...
arxiv.org/abs/0709.4539
arxiv.org/abs/quant-ph/0...

1 10 Tue Aug 06 12:41:04 +0000 2019

Tweet 2.17:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And, arguably, Yuan Liang Lim's, and Jungsang Kim and Changsoon Kim.
arxiv.org/abs/quant-ph/0...
arxiv.org/abs/0711.3866

0 8 Tue Aug 06 12:41:18 +0000 2019

Tweet 2.18:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Then a few years later, from Naomi Nickerson in Simon Benjamin's group, and for ion traps from Chris Monroe's group, growing out of the work of Jungsang.
nature.com/articles/ncomm...
link.aps.org/doi/10.1103/Ph...

0 9 Tue Aug 06 12:41:42 +0000 2019

Tweet 2.19:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This paper gets only a modest amount of love, but represents perhaps(?) the first attempt to do a full stack design, including taking into account distillation and QEC overhead. The microarchitecture even includes the ability to work around dead qubits!
arxiv.org/abs/0906.2686

↻0 ♡8 Tue Aug 06 12:41:59 +0000 2019

Tweet 2.20:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Yes, if you're paying close attention, I just copied a tweet from a couple of months ago: twitter.com/rdviii/status/. . .)

↻0 ♡8 Tue Aug 06 12:42:19 +0000 2019

Tweet 2.21:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Arguably, that paper by Thaddeus Ladd, Austin, Yoshi and me had a _negative_ influence; I believe at least one or two senior researchers shifted direction _away_ from practical quantum computing with error correction because of the huge resource demands in that.

↻0 ♡8 Tue Aug 06 12:42:41 +0000 2019

Tweet 2.22:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell But it was always intended to be a first "what if" paper, and many of the designs that followed from that use far fewer resources (qubits and classical hardware) as a result.

↻0 ♡5 Tue Aug 06 12:42:59 +0000 2019

Tweet 2.23:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Cody's paper is one such, and does a great job of laying out a structure for the architectural roles for various subsystems.
arxiv.org/abs/1010.5022

↻0 ♡7 Tue Aug 06 12:43:17 +0000 2019

Tweet 2.24:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So multicomputer is a popular, and relatively obvious, architectural choice, but the devil is in making the interconnect work. Ahsan, Jungsang and I worked on scheduling the interconnect during my year's sabbatical in Durham.
arxiv.org/abs/1512.00796

↻0 ♡7 Tue Aug 06 12:43:42 +0000 2019

Tweet 2.25:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We were all striving toward architectures with error correction. During the early part of this period, there was increasing awareness of the architectural difficulty of *executing* quantum error correction.

↻0 ♡7 Tue Aug 06 12:44:10 +0000 2019

Tweet 2.26:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I'm not even going to be able to *begin* to address QEC, except to point out two great introductions from Simon and Barbara Terhal. See esp. Tab. VIII in Simon's.
arxiv.org/abs/0905.2794
arxiv.org/abs/1302.3428

↻0 ♡8 Tue Aug 06 12:44:32 +0000 2019

Tweet 2.27:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Bravyi, Kitaev, Dennis, Landahl (one of the many Quantum Andrews) and Preskill proposed a weird topological idea shortly before I joined the field.
arxiv.org/abs/quant-ph/9. . .
arxiv.org/abs/quant-ph/0. . .

↻0 ♡8 Tue Aug 06 12:44:56 +0000 2019

Tweet 2.28:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Which became maybe-physically-buildable with the work of Raussendorf.
arxiv.org/abs/quant-ph/0. . .

↻0 ♡7 Tue Aug 06 12:45:11 +0000 2019

Tweet 2.29:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Austin latched onto that, and has become our paladin, working to make it all achievable. It's impossible to express how much *work* Austin has done in the last decade. This 54-page paper only scratches the surface.
arxiv.org/abs/1208.0928
↻0 ♡6 Tue Aug 06 12:45:35 +0000 2019

Tweet 2.30:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell This Nature paper gives a hint of how much influence Austin has on the design of physical computers inside Google, though.
nature.com/articles/natur...
↻0 ♡10 Tue Aug 06 12:46:02 +0000 2019

Tweet 2.31:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Simon and the group that has coalesced around him have worked to shrink resource requirements, again harder than words can convey.
iopscience.iop.org/article/10.108...
↻0 ♡7 Tue Aug 06 12:46:26 +0000 2019

Tweet 2.32:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Dominic Horsman, Austin, Simon and I found an improvement that is really gaining traction, known as lattice surgery.
arxiv.org/abs/1111.4022
↻0 ♡9 Tue Aug 06 12:46:42 +0000 2019

Tweet 2.33:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Overall, there is broad but not universal consensus that these surface codes are the most architecturally practical, and many groups are working to *build* these systems.
↻0 ♡6 Tue Aug 06 12:47:05 +0000 2019

Tweet 2.34:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii

@skdh @earltcampbell Simon and Austin worked with another group that proposed a football field-sized quantum computer, which is indeed what it might take.
advances.sciencemag.org/content/3/2/e1...
↻0 ♡9 Tue Aug 06 12:47:19 +0000 2019

Tweet 2.35:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell In some cases, these architectural designs are abstract enough to provide principles that guide all designs. In other cases, they are specific to one technology. Certainly all-optical has different demands.
↻0 ♡7 Tue Aug 06 12:48:48 +0000 2019

Tweet 2.36:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell The best integrated optical experiments might come from Jeremy O'Brien's group.
sciencemag.org/cgi/content/ab...
↻0 ♡9 Tue Aug 06 12:49:02 +0000 2019

Tweet 2.37:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell But the most complete system designs come, again, from Simon Devitt, Kae Nemoto, Ashley Stephens, et al. The scale of the latter of these is mind-boggling, and I wish I had been involved in that work!
arxiv.org/abs/0805.3592
arxiv.org/abs/0808.1782
↻0 ♡5 Tue Aug 06 12:49:20 +0000 2019

Tweet 2.38:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Kae herself took the lead on one NV-diamond architecture that to my eye looks very buildable, if NV centers can be fabbed with less human intervention.
journals.aps.org/prx/abstract/1...
↻0 ♡6 Tue Aug 06 12:49:44 +0000 2019

Tweet 2.39:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell David DiVincenzo – yes, *that* DiVincenzo – has worked on scalable architectures. I've seen pictures at conferences, but this is the best paper match I could find. arxiv.org/abs/1511.06138

↻0 ♡5 Tue Aug 06 12:50:02 +0000 2019

Tweet 2.40:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We discussed some of this back over a year ago, here on Twitter: twitter.com/rdviii/status/...

↻0 ♡4 Tue Aug 06 12:50:19 +0000 2019

Tweet 2.41:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And again recently: twitter.com/craiggidney/st...

↻0 ♡8 Tue Aug 06 12:50:34 +0000 2019

Tweet 2.42:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Finally, let me close again with one of mine: Simon and I wrote about the path to scalability a couple of years ago in IEEE Computer. ieeexplore.ieee.org/document/75623...

↻0 ♡4 Tue Aug 06 12:50:58 +0000 2019

Tweet 2.43:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Ugh, I never updated the arXiv version, and the published version is *very* different. I should fix that. arxiv.org/abs/1605.06951)

↻0 ♡3 Tue Aug 06 12:51:11 +0000 2019

Tweet 2.44:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Enough for tonight. I'm offline for a couple of days, but this should give you enough to read. And at this point, if you turn this into an article, I want coauthorship :-).

↻0 ♡16 Tue Aug 06 12:51:30 +0000 2019

Tweet 2.45:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Okay, I'm back in the saddle (though I'm allergic to horses). Let's do this. Next stage in our #QuantumComputerArchitecture discussion.

↻3 ♡13 Fri Aug 09 00:14:20 +0000 2019

Tweet 2.46:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We were talking about large-scale quantum computer architectures. Before we leave the topic, it would be remiss of me not to plug Kane and Kielpinski.

↻0 ♡5 Fri Aug 09 00:15:35 +0000 2019

Tweet 2.47:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Kielpinski's design, with Chris Monroe and Dave Wineland, is the ancestor of single-trap scalable ion systems. The Chuang orbit mentioned earlier designed architectures around this technology. nature.com/articles/natur...

↻0 ♡8 Fri Aug 09 00:15:57 +0000 2019

Tweet 2.48:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Kane's design for donors in Si is not just a technology, he proposed actual architectures with 1-D and 2-D layouts. nature.com/articles/30156

↻0 ♡5 Fri Aug 09 00:22:02 +0000 2019

Tweet 2.49:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This idea proved to be an enormous fabrication challenge; two decades on, Michelle Simmons leads the charge, working with Lloyd Hollenberg, Charles Hill, Michael Bremner, and a whole cast. advances.sciencemag.org/content/1/9/e1...

↻0 ♡6 Fri Aug 09 00:22:28 +0000 2019

Tweet 2.50:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The Copsey paper I mentioned (long ago now) led to QEC-focused designs based on both those technologies. It's hard to overstate the importance of those two papers.

↻0 ♡4 Fri Aug 09 00:22:59 +0000 2019

Tweet 2.51:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Importantly, Kane took into consideration the need for space for classical control and I/O AND the need to achieve scalability...

↻0 ♡3 Fri Aug 09 00:44:15 +0000 2019

3 Thread 3: Classical Control Systems

Tweet 3.1:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell which brings us to our next topic:
3. classical control systems
Let's throw in I/O with this.

↻0 ♡6 Fri Aug 09 00:44:27 +0000 2019

Tweet 3.2:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I/O here covers three meanings:
a. coaxing a photon from a quantum device, often entangled with a stationary qubit, to make long-distance entanglement;

↻0 ♡6 Fri Aug 09 00:44:44 +0000 2019

Tweet 3.3:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell b. measuring quantum states in whole or in part, whether for algorithmic results, quantum error correction, or teleportation; and
c. building a detailed quantum superposition based on large classical datasets.

↻0 ♡6 Fri Aug 09 00:45:07 +0000 2019

Tweet 3.4:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell To the surprise of many people, in most technologies, qubits are huge, especially when you incorporate the classical control structures and I/O pads (in solid state systems). A few hundred in a single device will be a challenge.

↻0 ♡6 Fri Aug 09 00:45:30 +0000 2019

Tweet 3.5:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Kane and Kielpinski were perhaps the first to propose systems that would reach these limits of individual device size, forcing us toward multicomputer architectures.

↻0 ♡5 Fri Aug 09 00:45:48 +0000 2019

Tweet 3.6:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I'm not going to talk technology much, but it's important to note that entangling between two ion traps was done by Moehring & Monroe a while
back.
nature.com/articles/natur...

↻0 ♡9 Fri Aug 09 00:46:13 +0000 2019

Tweet 3.7:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And Narla, Schoelkopf, Devoret just recently between two separate superconducting chips in the same fridge.
journals.aps.org/prx/abstract/1...

↻0 ♡6 Fri Aug 09 00:46:32 +0000 2019

Tweet 3.8:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The other thing you have to worry about, besides the technological basis,

is the interconnect topology, scheduling and resource consumption; hence my thesis and related work.

↻0 ♡5 Fri Aug 09 00:47:02 +0000 2019

Tweet 3.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell If you're doing this in optics, of course, you need a way to switch those photons around, and Jungsang Kim knows this better than anybody. ieeexplore.ieee.org/abstract/docum...

↻0 ♡4 Fri Aug 09 00:49:39 +0000 2019

Tweet 3.10:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell This is also the basis for quantum networking, whether system area networks (as in multicomputers) or for the Quantum Internet. wiley.com/en-us/Quantum+...

↻0 ♡6 Fri Aug 09 00:49:59 +0000 2019

Tweet 3.11:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Ha! You didn't really think I was going to go through this whole thread without plugging my book, did you?!?)

↻0 ♡12 Fri Aug 09 00:50:20 +0000 2019

Tweet 3.12:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Apologies to the Americans (north, south, wherever) who are in or going to bed, but now it's time to start picking up the European early risers.

↻0 ♡4 Fri Aug 09 04:13:30 +0000 2019

Tweet 3.13:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell More #QuantumComputerArchitecture coming up.

↻0 ♡5 Fri Aug 09 04:14:09 +0000 2019

Tweet 3.14:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Okay, so that's a. above. What about measurement? Ugh, that's such a hassle, at the physical level...measurements are slow and inaccurate in most technologies, compared to the actual gates.

↻0 ♡4 Fri Aug 09 04:14:31 +0000 2019

Tweet 3.15:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell At the algorithm level, you only have to measure each qubit once, generally speaking. But some things involving byproduct operators, where you need to select your next operation based on the outcome of the current one.

↻0 ♡5 Fri Aug 09 04:14:52 +0000 2019

Tweet 3.16:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell That's called "feedforward", and it's tough, especially in solid-state systems, because the signal integration times for measurement can be on the order of the memory coherence time. It's one of the biggest open architectural problems across multiple platforms.

↻0 ♡4 Fri Aug 09 04:15:10 +0000 2019

Tweet 3.17:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell It's a challenge in today's systems already, but more importantly, for large-scale, fault-tolerant systems, we need it to make quantum error correction work, and it's going to have to be both fast and accurate.

↻0 ♡5 Fri Aug 09 04:15:33 +0000 2019

Tweet 3.18:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell But rather than the tech, let's talk about the control. It has been suggested the output problem presents a challenge. Fortunately, as the systems

themselves scale, for the most part, the classical control logic scales linearly.

↻0 ♡4 Fri Aug 09 04:15:53 +0000 2019

Tweet 3.19:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Again, let's turn to Simon and Austin. There is *zero* doubt that they are the only ones working on this problem, but I think some of those efforts are proprietary, and I couldn't find other literature on the topic.

↻0 ♡4 Fri Aug 09 04:16:13 +0000 2019

Tweet 3.20:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Rather than the I/O bandwidth itself, the question is whether we will be able to do the calculations necessary to decode error syndromes and correct the state in real time.

↻0 ♡6 Fri Aug 09 04:16:36 +0000 2019

Tweet 3.21:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Some quantum codes have very straightforward decoding, but the surface code that we have fallen in love with (2-D or 3-D) presents a very difficult problem. Simon looked at this a full decade ago, and concluded yes, it's feasible.
arxiv.org/abs/0906.0415

↻0 ♡6 Fri Aug 09 04:16:56 +0000 2019

Tweet 3.22:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Austin has worked on the decoder more than anyone, looking for the simplest and the most effective methods. Somewhere, I think on a Google research blog, I have seen a photo of Austin and others with a

↻0 ♡5 Fri Aug 09 04:17:41 +0000 2019

Tweet 3.23:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell rig of FPGA boards emulating an error syndrome stream and executing a simplified decoder in real time using FPGAs, as a demonstration that yes, it works. But I couldn't find that among the absolute torrent of Austin's work.

↻0 ♡6 Fri Aug 09 04:18:00 +0000 2019

Tweet 3.24:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell More prosaically, the classical control hardware scales linearly, but currently still has a high per-qubit cost. But it has come down from a 19" rack full per qubit, to an FPGA or two in the last decade.

↻0 ♡4 Fri Aug 09 04:18:23 +0000 2019

Tweet 3.25:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Martinis's group (I think) even published elements of their FPGA design as open source, if I recall, but I couldn't dig that up, either.

↻0 ♡4 Fri Aug 09 04:18:47 +0000 2019

Tweet 3.26:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell But while looking for that, I found this review by David Reilly on classical control of solid-state qubits that I hadn't seen before. What I'm after is probably buried in those references.
nature.com/articles/npjqi. . .

↻2 ♡6 Fri Aug 09 04:19:07 +0000 2019

Tweet 3.27:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Moreover, while the idea of multiplexing control of qubits on-chip is an automatic thought, it's hard due to the fact that many semiconductor circuits don't work at the millikelvin temps the quantum devices prefer. But people are working that problem, as well.

↻0 ♡5 Fri Aug 09 04:19:25 +0000 2019

Tweet 3.28:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Sorry I'm not more help on this area, it's just outside my usual trodden path. Let's leave it here.

↻0 ♡2 Fri Aug 09 04:52:41 +0000 2019

Tweet 3.29:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So, c. building superpositions from classical data. Without some solution to this problem, quantum systems will be limited to problems with a small problem description but large computational space, such as e.g. chess/shogi/go or small molecule simulation.

↻1 ♡5 Fri Aug 09 04:53:08 +0000 2019

Tweet 3.30:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell In particular, quantum computing isn't going to work well for image recognition or any machine learning tasks with dataset-based learning until we fix this (but see caveat a little later).

↻1 ♡5 Fri Aug 09 04:53:30 +0000 2019

Tweet 3.31:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We want to take a big pile of classical data, put in a quantum superposition as an address, and receive as output a superposition of all of the data.

↻0 ♡4 Fri Aug 09 04:54:25 +0000 2019

Tweet 3.32:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The first description of the general idea I'm aware of is actually Fig. 6.9 in Mike & Ike.
amazon.com/Quantum-Comput...

↻0 ♡4 Fri Aug 09 04:54:49 +0000 2019

Tweet 3.33:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell It doesn't seem to have a reference; I don't know if they originated the idea or not. But I used it in one of my early papers on improving Shor's algorithm performance.

↻0 ♡6 Fri Aug 09 04:55:12 +0000 2019

Tweet 3.34:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Giovannetti, Lloyd and Maccone took a step toward making this practical, and coined the term "QRAM".
arxiv.org/abs/0708.1879v2
arxiv.org/abs/0807.4994

↻0 ♡9 Fri Aug 09 04:55:36 +0000 2019

Tweet 3.35:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell But there is still no proposed concrete implementation. I refer to this as the "billion dollar patent". Build it, and you're famous (and rich).

↻0 ♡6 Fri Aug 09 04:55:58 +0000 2019

Tweet 3.36:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell All right, that one was shorter than topics 1 & 2 from our list. Time for a break, then we'll take up #4.
twitter.com/rdviii/status/...

↻0 ♡7 Fri Aug 09 05:09:03 +0000 2019

4 Thread 4: NISQy Business

Joe Fitzsimons coined the term "NISQy business", and as of this writing has initiated a blog at http://nisqybusiness.com/, with more of a focus on the business of nascent quantum computing companies, whereas here I (briefly) addressed some of the near-term technical challenges.

Tweet 4.7 refers to the famous "tire tracks" diagram showing how U.S. government support for

research in IT has led to the development of numerous important industries within the overall IT field [7, 17, 18].

The first author of [53] is Jarrod McClean, and that of [3] is Eric R. Anschuetz. The first author of [103] is Zhikuan Zhao.

Tweet 4.1:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Let's pick up topic #4: noisy, intermediate-scale quantum technology, or NISQ. John Preskill, with his usual timeliness and insight, coined the term about two years ago, and people have latched on to it. arxiv.org/abs/1801.00862

0 ♡7 Fri Aug 09 06:22:16 +0000 2019

Tweet 4.2:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell It describes our current era, with tens of qubits and the fight to declare quantum supremacy. It's likely true that the first problems solved using quantum computers will be abstruse, of little direct value. We all know that; see Harrow & Montanaro. nature.com/articles/natur...

0 ♡6 Fri Aug 09 06:22:48 +0000 2019

Tweet 4.3:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And we know that there are problems on the far horizon that large-scale, fault-tolerant, fast quantum computers will solve, famously factoring of large numbers but numerous others. See Montanaro for the most recent, thorough list. nature.com/articles/npjqi...

0 ♡5 Fri Aug 09 06:23:09 +0000 2019

Tweet 4.4:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Along with Bacon & van Dam and the Quantum Algorithm Zoo mentioned earlier. m-cacm.acm.org/magazines/2010... quantumalgorithmzoo.org

0 ♡4 Fri Aug 09 06:23:31 +0000 2019

Tweet 4.5:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And so the challenge in front of us is to *find the boundary*. Where is the minimal machine and software combination that *customers will pay money for* and use to solve their pressing problems?

0 ♡3 Fri Aug 09 06:23:51 +0000 2019

Tweet 4.6:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell That sounds nakedly capitalist, and it is. Our goal here is to seed an entire industry, where the computational outcomes are used to make the world a better place, which means creating products delivered to the public.

0 ♡5 Fri Aug 09 06:24:22 +0000 2019

Tweet 4.7:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Governments have seeded entire industries before, famously the airlines via postal services, and the Internet and much of our modern IT industry (which lets me talk to you now). cccblog.org/2016/07/27/the...

0 ♡5 Fri Aug 09 06:24:52 +0000 2019

Tweet 4.8:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell In the short run, this means finding hybrid quantum-classical algorithms, breaking down large problems into subproblems or iterate-able problems. This field is *wide open*.

0 ♡6 Fri Aug 09 06:25:12 +0000 2019

Tweet 4.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Alán Aspuru-Guzik's team has been working this problem for VQE, the variational quantum eigensolver.

iopscience.iop.org/article/10.108...
↻0 ♡5 Fri Aug 09 06:25:59 +0000 2019

Tweet 4.10:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell As well as working on NISQy factoring.
twitter.com/A_Aspuru_Guzik...
arxiv.org/abs/1808.08927
↻0 ♡4 Fri Aug 09 06:26:15 +0000 2019

Tweet 4.11:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Martin Suchara, Fred Chong, Graeme Smith and others are thinking about hybrid quantum-classical supercomputing systems, making concrete ideas that have been floating around.
sc18.supercomputing.org/proceedings/wo...
↻0 ♡5 Fri Aug 09 06:26:38 +0000 2019

Tweet 4.12:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell While Bravyi, Smith and Smolin quantitatively examined this tradeoff in one specific case.
journals.aps.org/prx/abstract/1...
↻0 ♡6 Fri Aug 09 06:26:56 +0000 2019

Tweet 4.13:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell This is the caveat I mentioned above – if you want to do big data on a quantum computer, can you break it down into bite-sized chunks where the QC can help?
↻0 ♡6 Fri Aug 09 06:27:15 +0000 2019

Tweet 4.14:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Also, there are weird mathematical tricks you can play with noisy outcomes to estimate what the outcome would have been in a perfect world, as the IBM team has shown.
nature.com/articles/s4158...
↻1 ♡6 Fri Aug 09 06:27:37 +0000 2019

Tweet 4.15:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell *This* is where the battle is being fought right now. And bringing things full circle...I don't think we have the programming tools, indeed, even the vocabulary to think about and describe these systems as they span the spectrum from NISQ to full scale.
↻0 ♡8 Fri Aug 09 06:28:01 +0000 2019

Tweet 4.16:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell So the end of this epic tweetstorm is in sight. We'll come back tonight or tomorrow with one more round on programming, then do a review & wrap-up.
↻0 ♡7 Fri Aug 09 06:28:26 +0000 2019

Tweet 4.17:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Oh, back in the I/O section, I forgot to include recent work from Zhikuan Zhao of Joe Fitzsimons' group, on building superpositions from classical data. It's on my own stack to read!
arxiv.org/abs/1804.00281
↻0 ♡5 Fri Aug 09 09:09:14 +0000 2019

Tweet 4.18:

 Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell And one (near) final name that hasn't yet managed to pop up, but we would be remiss to ignore: Jake Taylor, now at the White House OSTP.
nature.com/articles/nphys...
↻0 ♡5 Fri Aug 09 11:35:50 +0000 2019

5 Thread 5: Return to Programming

In tweet 5.7, I should have cited Tannu, as well [85]. This is an important paper on qubit variability, and its omission was unintentional. The first author of [64] is Joe O'Gorman. The

first author of [11] is Titouan Carette.

Tweet 5.1:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We started this Homeric epic on the topic of programming quantum systems, and that's where we're going to end. It turns out to be of utmost relevance both to large-scale systems and, urgently, to NISQ. It's also critical for education.

↻0 ♡4 Fri Aug 09 11:36:15 +0000 2019

Tweet 5.2:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell For the real systems available today, we have Qiskit, PyQuil, etc. Libraries and compilers for, essentially, assembly languages for quantum computers. These are awesome, and necessary, toolkits.

↻0 ♡4 Fri Aug 09 11:36:39 +0000 2019

Tweet 5.3:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Remember back when I was talking about architecture-aware compilation, and graph embedding? The idea is important in the abstract, and absolutely critical for making programs run on IBM's and Rigetti's current processors.

twitter.com/rdviii/status/...

↻0 ♡5 Fri Aug 09 11:37:06 +0000 2019

Tweet 5.4:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Alwin Zulehner and Alexandru Paler, of Robert Wille's group specializing in reversible computing (which has both deep and practical connections to quantum), built a toolkit and tested it against real machines.

arxiv.org/abs/1712.04722

arxiv.org/abs/1806.07241

↻0 ♡5 Fri Aug 09 11:37:30 +0000 2019

Tweet 5.5:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell One of the critical characteristics of those computers is that each qubit and each coupler is different. So, we need *error aware* compilation. My group started working on that topic a while back, focusing on daily-use arithmetic circuits rather than abstract benchmarking.

↻0 ♡4 Fri Aug 09 11:37:59 +0000 2019

Tweet 5.6:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell We addressed specific aspects of the problem, including experimentally assessing our ability to _predict_ error rates on the IBM machines. We also focused on heuristics that will scale, and we hope provide good-enough answers.

arxiv.org/abs/1903.10963

↻0 ♡4 Fri Aug 09 11:38:34 +0000 2019

Tweet 5.7:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Unbeknownst to us, Margaret Martonosi's group was working on the same topic. They took a broader approach, and covered several machines and algorithms very thoroughly.

arxiv.org/abs/1905.11349

↻0 ♡4 Fri Aug 09 11:38:58 +0000 2019

Tweet 5.8:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Sadly for us, our paper was rejected, while theirs was (very deservedly) accepted to a top architecture conference. Ours is currently under review again. I think the two papers are complementary, and expect to see ours in print as well.

↻0 ♡4 Fri Aug 09 11:39:37 +0000 2019

Tweet 5.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Oh, and the need for compilation heuristics? This graph embedding problem is NP-complete. I had long assumed it was, but to my surprise, that apparently was never proven until last year.

doi.acm.org/10.1145/3168822
↻0 ♡5 Fri Aug 09 11:40:00 +0000 2019

Tweet 5.10:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Not being a theorist myself, that's a result I'm happy to read and apply; it's the kind of paper I'm unlikely to write.)

↻0 ♡4 Fri Aug 09 11:40:35 +0000 2019

Tweet 5.11:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And Matthew Amy, Dmitri Maslov, Michele Mosca and Martin Roetteler worked on optimizations as well, back in the intermediate period.
arxiv.org/abs/1206.0758

↻0 ♡4 Fri Aug 09 11:41:00 +0000 2019

Tweet 5.12:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell All this is great. But I honestly don't think that the current generation of production tools are what we will use ten or twenty years from now. We need better theory of programming, and better tools for writing and debugging programs.

↻0 ♡5 Fri Aug 09 11:41:25 +0000 2019

Tweet 5.13:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Lloyd Hollenberg's group (from whence Simon and Austin came) is building a fantastic toolset, called QUI, intended to support intuition in programming.
qui.research.unimelb.edu.au

↻0 ♡4 Fri Aug 09 11:41:45 +0000 2019

Tweet 5.14:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And you remember the Dagstuhl seminar I mentioned? Reports are available.
dagstuhl.de/en/program/cal...

drops.dagstuhl.de/opus/volltexte...

↻0 ♡4 Fri Aug 09 11:42:05 +0000 2019

Tweet 5.15:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Earl Campbell, who started me down this thread, has his hand in a whole slew of theory topics that advance our understanding of how to compute on top of error correction. He was there.
journals.aps.org/pra/pdf/10.110...

↻0 ♡4 Fri Aug 09 11:42:23 +0000 2019

Tweet 5.16:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So was Olivia Di Matteo, working on circuit synthesis and (to my pleasant surprise) error tolerance in QRAM.
arxiv.org/abs/1606.07413
arxiv.org/abs/1902.01329

↻0 ♡6 Fri Aug 09 11:42:43 +0000 2019

Tweet 5.17:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell There were a *bunch* of folks there I admire, some with bold visions for what it means to program quantum systems. One such is Robert Rand, whose thesis is on formally verifying quantum programs.
repository.upenn.edu/cgi/viewconten...

↻0 ♡4 Fri Aug 09 11:43:04 +0000 2019

Tweet 5.18:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Another advanced concept is the Scalable ZX calculus, from Dominic Horsman's group and orbit. It supports rewrite-based optimization that is provably correct.
arxiv.org/abs/1905.00041

↻0 ♡4 Fri Aug 09 11:43:24 +0000 2019

Tweet 5.19:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Earlier this year, an experimentalist I *deeply* admire told me that it's way too early to early to be working on high-level programming languages and tools, that low-level optimization will be required for the foreseeable future.

↻0 ♡3 Fri Aug 09 11:43:46 +0000 2019

Tweet 5.20:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I couldn't possibly disagree more. Building these systems takes *insight*, and none of that comes for free; it takes *time* and *work*.

↻0 ♡4 Fri Aug 09 11:44:03 +0000 2019

Tweet 5.21:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Moreover, I think we need to build tools that will support the *intuition* of the #QuantumNative students we are educating today.

↻1 ♡6 Fri Aug 09 11:44:21 +0000 2019

Tweet 5.22:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And, we need software engineering tools that will scale to large programs, and ways of *debugging* quantum software. I think these tools will be entirely new.

↻0 ♡3 Fri Aug 09 11:44:42 +0000 2019

Tweet 5.23:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So, building scalable systems is an end-to-end problem, requiring many skills. "It takes a village," someone said in a different context. Come join us, we can use the help!

↻0 ♡5 Fri Aug 09 11:45:03 +0000 2019

Tweet 5.24:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Okay, let me end there. I don't know about you, but I'm pretty much exhausted at this point. I'll come back tomorrow with a recap and some final thoughts. Good night!

↻0 ♡8 Fri Aug 09 11:45:21 +0000 2019

6 Thread 6: Wrap-Up

A YouTube URL was removed from tweet 6.24.

Tweet 6.1:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Welcome to the final day of your master class in #QuantumArchitecture! There is no final exam, but if you're a student, I just wrote your bibliography for you.

↻0 ♡4 Sat Aug 10 00:30:56 +0000 2019

Tweet 6.2:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Author's privilege: I've been saving for the end a plug for the Ph.D. thesis of my student Shota Nagayama, whose large-scale architecture includes a different approach to dealing with defective qubits,

↻0 ♡3 Sat Aug 10 00:32:25 +0000 2019

Tweet 6.3:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell and detailed mechanisms for architectures that depend on different error correcting codes for different tasks. arxiv.org/abs/1704.02620

↻0 ♡4 Sat Aug 10 00:32:39 +0000 2019

Tweet 6.4:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So let's go back and review some of the principles of quantum computer architectures. Most of these have classical precedents.

↻0 ♡4 Sat Aug 10 00:32:59 +0000 2019

Tweet 6.5:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell A. basic gate-level parallelism. When I joined the field, it was widely but not yet universally understood that we *have* to have this for QEC to work. I think it's now universally known.

↻0 ♡4 Sat Aug 10 00:41:09 +0000 2019

Tweet 6.6:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell B. architecture-aware compilation. Graph theory-based techniques are useful here, and there are echoes of classical dataflow architectures and dependency graphs. The abstraction underlying this is still poorly understood by many.

↻0 ♡4 Sat Aug 10 00:41:26 +0000 2019

Tweet 6.7:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Dataflow architectures in their purest form have passed on, but the principle is deep and fundamental in both hardware and software.
en.wikipedia.org/wiki/Dataflow
en.wikipedia.org/wiki/Dependenc...
)

↻0 ♡4 Sat Aug 10 00:41:52 +0000 2019

Tweet 6.8:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell C. application-level parallelism and resource tradeoffs. Scheduling of computations and the application of Amdahl's Law are practically subfields in computer architecture.

↻0 ♡4 Sat Aug 10 00:42:09 +0000 2019

Tweet 6.9:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell D. scalability requires distribution. This idea led us to multicomputer architectures – independent units must have autonomy while sharing data in large computations.

↻0 ♡4 Sat Aug 10 00:42:37 +0000 2019

Tweet 6.10:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell E. constant factors matter. I lost track of the number of people in my early days who stared at me uncomprehendingly and replied, "But it's exponentially faster." This misunderstanding in particular led to non-viable designs.

↻0 ♡4 Sat Aug 10 00:42:58 +0000 2019

Tweet 6.11:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell One thing I like to say is that the *principles* are the same, but the technological differences mean that the *answers* look very different.

↻0 ♡3 Sat Aug 10 00:43:17 +0000 2019

Tweet 6.12:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Overall, there is much for the physicists to learn from the computer engineers, and vice versa. It would be a help for the physicists to take undergrad and graduate computer architecture classes.
amazon.com/Computer-Organ...
amazon.com/Computer-Archi...

↻0 ♡5 Sat Aug 10 00:43:38 +0000 2019

Tweet 6.13:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell So, are we there yet? Have the vision, math and technology come together? In my 2006 thesis, I commented that "We are, in effect, in the time of Babbage asking what Knuth, Lampson and Torvalds will do with the machines we build," but maybe flight is a better analogy.

↻0 ♡5 Sat Aug 10 00:44:16 +0000 2019

Tweet 6.14:


Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Are our architectures above like da Vinci's flying machines, where the vision was there but the math and technology

weren't yet? Or Samuel P. Langley, with so much right about his organizational approach, which we might call Open Science today, but the wrong technology?

↻0 ♡2 Sat Aug 10 00:44:51 +0000 2019

Tweet 6.15:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I prefer to think we're in the time of the Wright brothers, going back and examining everything we're told, applying a scientific and engineering mindset, solving *all* the problems, and putting the first ones in the air.

↻0 ♡2 Sat Aug 10 00:45:13 +0000 2019

Tweet 6.16:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell (Their legacy afterwards was more problematic, but they certainly set off the revolution.)

↻0 ♡2 Sat Aug 10 00:45:29 +0000 2019

Tweet 6.17:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell All right, by now either you're on board with the overall message here, or you're not. But to find out if I'm way off base, just now I conducted a sanity check.

↻0 ♡3 Sat Aug 10 00:45:43 +0000 2019

Tweet 6.18:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell I went to duckduckgo.com, where my searches should be anonymous, and searched for "scalable quantum computer architecture". duckduckgo.com/?q=scalable+qu...

↻0 ♡3 Sat Aug 10 00:46:04 +0000 2019

Tweet 6.19:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The first few pages will find you the Microsoft Svore group, the Berkeley Kubi group, our "Blueprint" paper, some things from the Monroe-Kim-Brown orbit I didn't cite above, Michelle Simmons' team, some additional work from Misha Lukin's team, the football field paper.

↻0 ♡3 Sat Aug 10 00:46:29 +0000 2019

Tweet 6.20:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell Opening an incognito window and going to Google Scholar, I got Kielpinski, Monroe, Nemoto, Oskin, Copsey, Yao-Taylor-Jiang-Lukin all in the first page.

↻0 ♡3 Sat Aug 10 00:46:47 +0000 2019

Tweet 6.21:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell A couple of things I failed to cite, but I'd say that more or less validates the overall thrust here. (After about 150 tweets, that's a relief.)

↻0 ♡3 Sat Aug 10 00:47:09 +0000 2019

Tweet 6.22:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell About a third of the people I've cited here are on Twitter, but I deliberately didn't tag them in. You can find them if you try. And of course you are _all_ welcome to extend or refute what I've written!

↻0 ♡3 Sat Aug 10 00:47:27 +0000 2019

Tweet 6.23:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell And with that, we come to the end. Thank all y'all for sticking with me. I hope you found something useful here, and that creating this thread was worth my time!

↻0 ♡5 Sat Aug 10 00:47:44 +0000 2019

Tweet 6.24:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell The End

(swirling Erich Wolfgang Korngold music as the credits roll and the most un-Errol Flynn-like person you know rides off into the sunset)

↻0 ♡8 Sat Aug 10 00:48:09 +0000 2019

7 Thread 7: Coda and Postscript

Tweet 7.5 was added approximately thirty hours after the completion of this tweetstorm, but seems to be an important reference to retain.

The expression "tl;dr" is Internet slang for, "too long; didn't read."

A YouTube URL was removed from tweet 7.9.

Tweet 7.1:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Coda: okay, okay, I know I threw a complete bus, driver and all, at you. By my count, I've included about 97 references, and I know not all of you are going to read that many. So, if you must have the tl;dr:
↻0 ♡3 Sat Aug 10 00:48:32 +0000 2019

Tweet 7.2:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell tl;dr:
If you want to understand the state of affairs in quantum computing, you could do much worse than these six:
1. tdl et al., "Quantum Computers"
2. rdv & dch, "Blueprint"
3. sjd et al., "Beginners"
4. Montanaro, "Algorithms"
5. Preskill, "NISQ"
6. Harrow, "Supremacy"

↻13 ♡27 Sat Aug 10 00:49:24 +0000 2019

Tweet 7.3:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell (yes, three of those are by me and/or my friends & collaborators, and the first one desperately needs an update, but so it goes.)
↻0 ♡2 Sat Aug 10 00:49:42 +0000 2019

Tweet 7.4:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Links:

arxiv.org/abs/1009.2267
m-cacm.acm.org/magazines/2013...
arxiv.org/abs/0905.2794
nature.com/articles/npjqi...
arxiv.org/abs/1801.00862
nature.com/articles/natur...
↻1 ♡6 Sat Aug 10 00:49:59 +0000 2019

Tweet 7.5:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Good grief, I forgot the Chong-Franklin-Martonosi survey on programming languages. That should definitely be on this minimal reading list, and should have been brought up earlier.
nature.com/articles/natur...
↻2 ♡3 Sun Aug 11 10:44:30 +0000 2019

Tweet 7.6:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell Postscript (yes, both a coda and a postscript! Two for the price of one!)
↻0 ♡1 Sat Aug 10 00:50:20 +0000 2019

Tweet 7.7:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell It seems to be customary to follow up popular postings with a "feed me" button of some sort. I'm not an independent creator, so I don't need money directly. What I want is for you – *especially* if you're building systems –
↻0 ♡1 Sat Aug 10 00:50:43 +0000 2019

Tweet 7.8:

Rod Van Meter @rdviii
in reply to tweet by @rdviii
@skdh @earltcampbell is to *read* the lit, *use* the lit, *cite* the lit. And, if you're in a position to do so, invite the people listed here to come give talks at your institutions, and maybe even collaborate!
↻0 ♡6 Sat Aug 10 00:51:03 +0000 2019

Tweet 7.9:

 Rod Van Meter @rdviii

in reply to tweet by @rdviii

@skdh @earltcampbell That is all.

↻0 ♡4 Sat Aug 10 00:51:17 +0000 2019

Conclusion

Obviously, this article represents my personal opinion about the importance of various topics. It also depends on my recollection of certain events, and we know that memory is notoriously unreliable. However, I believe that everything that is historical fact is well supported, and everything that is opinion is easily recognized as such.

As noted, this article is intended to be read in electronic form and interactively, making use of the inline URL links. Where possible, I have used links that I expect to be long-lived; most are arXiv, ACM, IEEE, APS or Nature links. However, links have a habit of breaking, so for the record (and for the indexers) let me cite the papers here in their final (e.g., journal) form.

The tl;dr list includes [14, 22, 32, 49, 56, 72, 91]. The papers cited in Sec. 1 include [6, 12, 13, 15, 25, 30, 38, 42, 71, 77–79, 83, 84, 91, 92, 94, 99–102]. The papers cited in Sec. 2 include [1, 5, 8, 16, 19, 20, 22, 26, 35, 36, 39–41, 45, 46, 48–51, 54, 61, 63, 65–68, 74, 76, 81, 87, 88, 90, 93, 95–98]. The papers and books cited in Sec. 3 include [21, 28, 29, 47, 55, 60, 62, 75, 89]. The papers cited in Sec. 4 include [3, 4, 9, 32, 44, 53, 56, 72, 82, 86, 103]. The papers cited in Sec. 5 include [2, 11, 23, 24, 57, 58, 64, 69, 73, 80, 104]. The papers and books cited in Sec. 6 include [34, 59, 70].

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