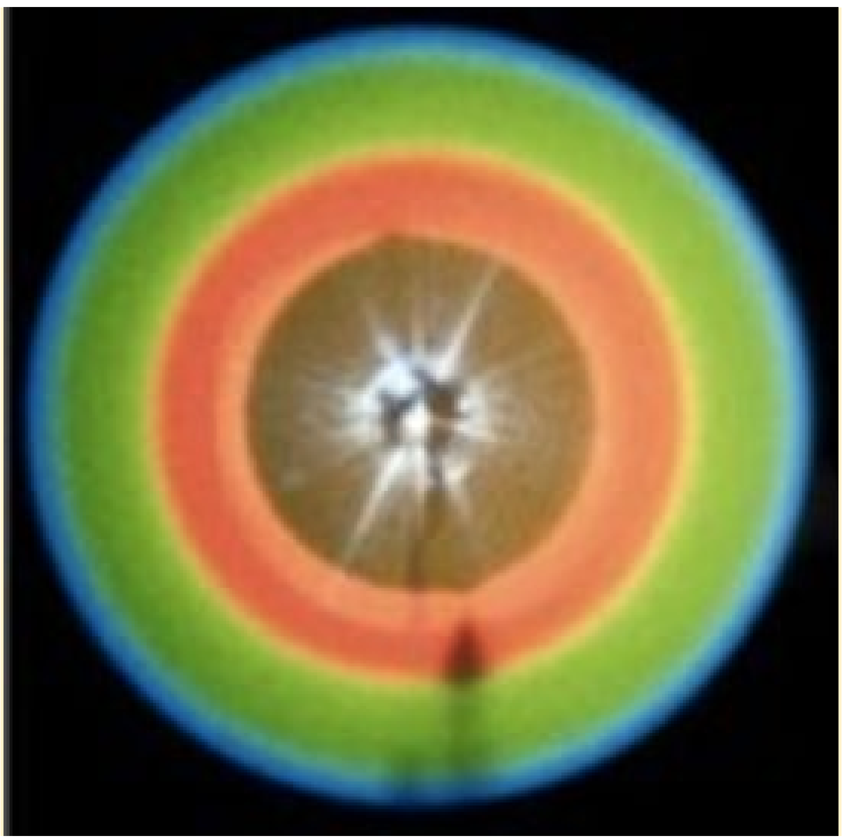
Single-Photon Measurement Infrastructure for Quantum Applications (SPMIQA): Needs and Priorities



Full spectrum light produced via spontaneous parametric downconversion. This light—generated two photons at a time—enables heralding of single photons, the basis of many single-photon sources. (Photo Credit: A. Migdall/NIST)

Acknowledgments

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- Jack Berg, PsiQuantum
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About the Quantum Economic Development Consortium

The Quantum Economic Development Consortium (QED-C®) is an industry-driven consortium managed by SRI International. The consortium seeks to enable and grow the quantum industry and associated supply chain. QED-C is supported by the National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce and more than 175 members, including component manufacturers and suppliers, software and hardware system developers, researchers, professional service providers, and end users. Consortium membership represents companies, universities, federally funded research and development centers, government, and other stakeholders. Learn more about QED-C at quantumconsortium.org.

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1. Executive summary

As the fields of quantum computing, quantum sensing, and quantum communication mature into engineering disciplines, a robust measurement infrastructure is needed that is available to all developers of quantum technology. This requirement for measurement capabilities is immediate, and will grow more urgent as planned use cases, such as quantum networks, are developed and brought online. Thus, it is essential to address this need now. An accurate, easily accessible, fast-turnaround measurement capability is key to accelerating the development process of quantum components. This need is particularly acute for single-photon sources and detectors, which are critical components of many quantum systems for sensing, communications, and computing. At present, characterizing the performance of these components is not straightforward, and new measurement methods and tools need to be developed and/or existing methods must be more widely shared. It is within this context that an invitation-only QED-C workshop was held (September 2021) with the goals of (1) understanding the quantum industry's measurement needs for single-photon sources and detectors, (2) assessing the state of the art in single-photon source and detector characterization, and (3) clarifying the gaps in measurement capabilities.

Quantum industry stakeholders are faced with the dual challenges of not only commercializing emerging quantum technologies, but also implementing or developing their own internal metrology tools[1] for validating device and component performance. The underlying metrology services pertinent to single-photon sources and detectors are currently being formulated by national metrology institutions such as the National Institute of Standards and Technology (NIST), which have unique capabilities and a mission to support industry needs. By bringing together quantum technology developers and metrology experts from industry, government, and academia, the workshop collected the information needed to help prioritize single-photon sources and detector measurement service needs. This report describes the highest-priority measurement needs of quantum device and system researchers and developers, as well as recommendations for addressing the needs identified in the workshop.

To develop the necessary metrology and metrology services required to promote advances in single-photon source and detector technology, a committee of experts was formed to summarize the issues and needs brought forth from the workshop, categorize them to identify specific research tasks, and highlight activity and funding priorities. With input from the workshop attendees, the committee identified four focus areas that would significantly advance the development and adoption of single-photon technologies and developed priority recommendations (see Section 4) for each of these areas:

1. **Information:** The commercial development of single-photon technologies is being hindered by a lack of clearly defined single-photon metrics and measurement methods. A common language of terms and a compendium of best metrological practices is needed, as well as a means to disseminate that information and related expertise.

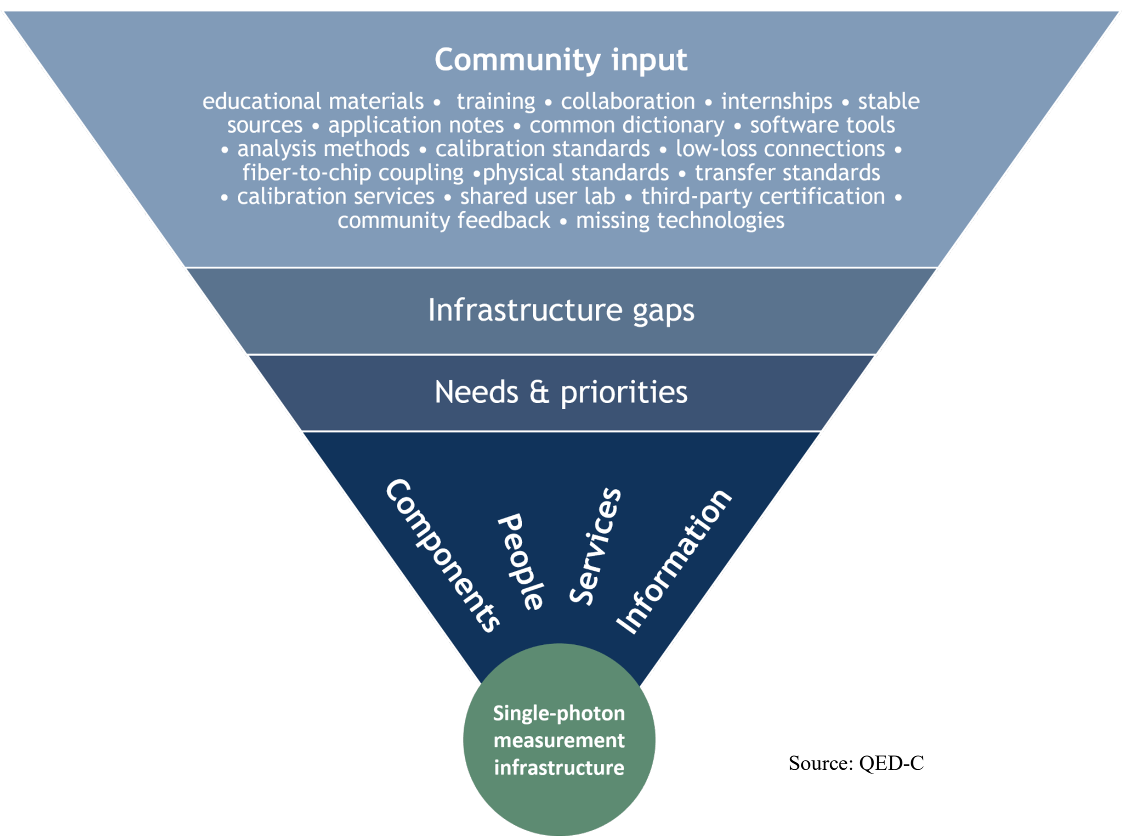
2. **People:** Although quantum information development is driven by pockets of deep expertise, there is an overall expertise deficit across large parts of the community. Addressing this deficit requires a concerted and coordinated effort to broaden participation of all communities involved in these quantum efforts. Thus, there is a need for an accessible training network to provide appropriate best practices to the wider single-photon technology community, for active outreach to underrepresented communities, and for introductory training in appropriate

[1] Metrology is the science of measurement.

fundamentals [1]. A specific goal should be to broaden participation of all communities involved in these quantum efforts.

3. **Components:** As single-photon technologies scale up and "proof of principle" demonstrations progress into common adoption, there will be an increasing need for significantly improved performance from classical system components so that they meet quantum system requirements. There is a need for standardized, reliable, repeatable, and widely available off-the-shelf components relevant to single-photon technologies such as laser sources, fiber connectors, attenuators, and detectors. These building blocks will enable consistent performance across laboratories and applications as systems scale up, which in turn will facilitate pathways to mass-market manufacturability.

4. **Services:** Better access to calibration capabilities/services is needed, whether it is through national measurement labs, third-party labs, in-house equipment that maintains high accuracy (perhaps through some QED-C portal) or some other mechanism to access the expertise to ensure that high accuracy calibration can be made with confidence. In addition, rugged devices that do not need regular calibration, or that can be self-calibrated would facilitate pathways to market adoption and technology proliferation.



Visual representation of how to address measurement gaps and needs

2. Introduction

Nearly every significant advance in quantum information has involved single-photon technologies to some extent, and that trend is expected to continue as quantum technologies move from the laboratory to the marketplace. Single photons have several distinct advantages as qubits over their matter-based counterparts. Most notably, photons are particularly well suited to move information from one place to another, or one modality to another such as in quantum transduction. For this reason, single-photon technologies feature prominently in quantum communications systems and quantum networks, and photonic approaches to quantum computing have taken advantage of the ease with which photons can be manipulated. However, single photons also play a role in matter-based quantum technologies, and many quantum computing and quantum sensing approaches rely on single-photon technologies in support functions.

The many different roles photons play in quantum technologies require almost as many different types of single-photon sources. While true single-photon emitters are ideal, the controlled emission of exactly one photon at a precise time and with a precise set of properties is difficult to achieve. There are some promising approaches, and even some commercial devices are available (e.g., quantum dots), but the development of true single-photon emitters remains an active research area. For many quantum communications applications, an attenuated laser can serve as an approximation to a single-photon source. However, such sources are inadequate for other applications such as quantum networks, where entanglement between photons is required. Photon-pair sources based on spontaneous parametric downconversion or four-wave mixing can meet this need, and a few entangled-photon sources are now available commercially. Another type of source that is often discussed in the context of quantum light sources is the squeezed light source or, more broadly, the continuous variable light source. For this type of source, information is carried in the (continuous) electric field variable.

Just as there are many options for generating quantum states of light, there are also many approaches for the detection of those states. In all cases, the challenge is to transform a quantum event (absorption of a single photon) into an easily observable signal. One of the most convenient options is the avalanche photodiode (APD), in which a single photon can trigger a large electronic response in a strongly biased photodiode. Although APDs are relatively cost-effective, they are not as efficient as some other options, particularly at telecom wavelengths. In superconducting nanowire single-photon detectors (SNSPDs), a single photon incident on a narrow superconductor initiates a transition from the superconducting regime to a resistive regime that can be detected with a relatively simple circuit. In the transition-edge sensor (TES), a small superconducting material is operated near its critical temperature, and the absorption of a single photon changes the temperature of the sensor enough to change the superconducting properties of the sensor. Both the SNSPD and the TES can achieve nearly unit efficiencies, and the SNSPD can achieve very fast response times. However, both must be operated at cryogenic temperatures, increasing both the cost and complexity of the systems. An effort led by QED-C is currently being developed to further reduce this hurdle [2]. Finally, the detection of continuous variable states requires yet another type of detector. These states are typically detected by homodyne detectors, whereby the quantum signal is mixed with a strong local oscillator (typically a mode-matched laser). Single-photon detector technology is sufficiently mature that some types of detectors are commercially available (APDs and SNSPDs).

In addition to sources and detectors, single-photon technologies include supporting technologies. Cryogenic systems to house detectors fall into that category, but supporting technologies also include devices such as lasers and optical components for manipulating photons. Although versions of many of these components already exist, quantum applications often require improved performance. For example, the telecom industry has already developed many components that could be incorporated directly into single-photon applications, except that the telecom versions are often too lossy. Even the simple process of coupling two fibers together must be re-examined for the deployment of large-scale single-photon systems. Finally, there are efforts to transition many of the single-photon technologies discussed above to integrated photonic devices, where it is hoped that the smaller scale will not only reduce cost, but also improve performance.

Almost all single-photon technologies originating in university and government labs have been purpose-built for specific scientific works. Even today, the vast majority of end users of these technologies are in academia or government and are quite accustomed to building their own systems. Nevertheless, single-photon technologies are beginning to breach the commercial sector, with both large and small companies developing products to serve the community. While some of these companies are building sources and/or detectors for larger systems being developed in-house—e.g., photonic quantum computing and Quantum Key Distribution (QKD) systems—most are developing devices for the growing quantum technology market.

As single-photon technologies transition from the laboratory to the commercial sector, it is important to recognize factors that might hinder commercial development and, when possible, to take steps to reduce the impact of inevitable growing pains. One such area is single-photon metrology. The development of characterization tools for single-photon technologies has paralleled that of the sources and detectors, often in the very same laboratories; and it is clear that, to some extent, the companies developing single-photon technologies will also be using (and developing) relevant metrology technologies. However, most commercial developers are not as well equipped or trained as the academic and government laboratories. In addition, characterization tools developed for in-house use are less likely to be subjected to rigorous peer review, potentially leading to a lack of consistency among vendors. These problems are exacerbated by the fact that characterization tools for large-scale systems (e.g., quantum networks) are still in the earliest stages of development. All of these factors suggest that the commercial sector may find it difficult to take full advantage of the solid metrology foundation established by earlier research efforts, a problem that stands to impact both vendors and consumers of single-photon technologies.

It is within this context that an invitation-only QED-C workshop was held in September 2021 with the goals of (1) understanding the quantum industry’s measurement needs for single-photon sources and detectors, (2) assessing the state of the art in single-photon source and detector characterization, and (3) clarifying the gaps in measurement capabilities. This workshop was unique in the single-photon community because it did not focus on technology gaps around detectors and sources, but rather on measurement capabilities and, importantly, on how best to ensure the broad use of the best device characterization and measurement capabilities in the commercial sector, as well as the continued development of those capabilities. Section 3 summarizes the findings, with emphasis on device characterization needs and opportunities as identified by the workshop participants. This input was consolidated into four themes that are described in Section 4 along with specific actionable recommendations.

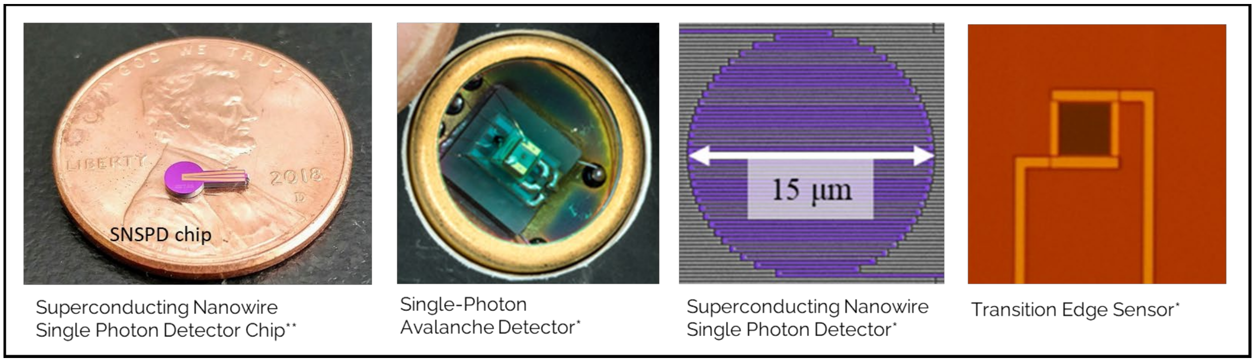
Source: QED-C

The Single-Photon Measurement Infrastructure for Quantum Applications workshop provided the quantum optics community with an opportunity to discuss technology gaps and needs related to single-photon metrology.

3. Community input

The Single-Photon Measurement Infrastructure for Quantum Applications workshop focused on single-photon detectors, sources, and applications and included a series of presentations from a representative cross-section of the community, followed by parallel, moderated discussion sessions. (See Appendix A.) Key findings from the workshop are summarized below.

A. Detectors



Examples of single-photon detectors.

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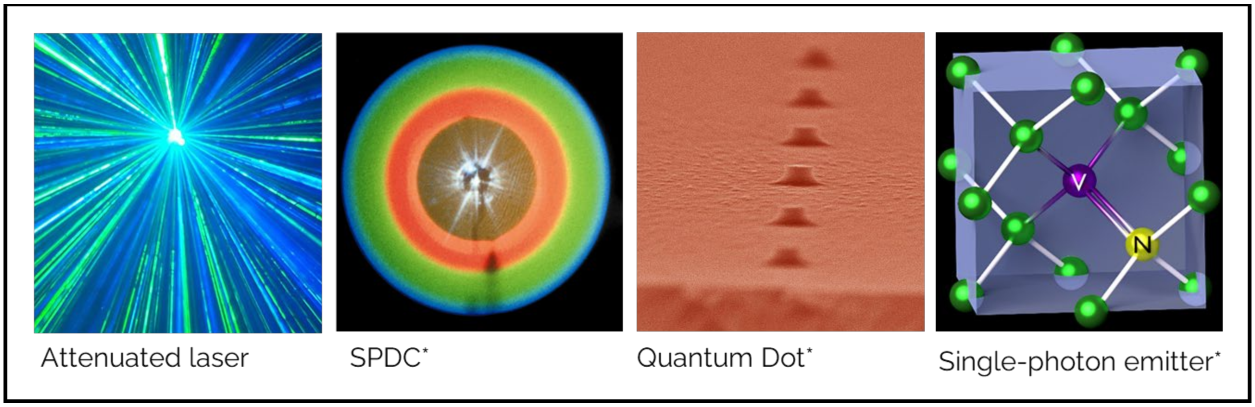
Detector technologies are more mature than source technologies. The historical financial investment in single-photon detector technologies has been significant because of classical (i.e., non-quantum-only) applications. As a result, detector metrics are fairly well understood, with the dominant needs focused on the increased detector performance required by quantum applications. In particular, for practitioners to realize maximum detector performance, four needs were identified that would provide immediate value to the greater community: (1) standardized measurement methods with documented uncertainties; (2) improved broadband efficiency calibration accuracy (<1 %); (3) documented and published best-practice "application notes;" and (4) increased availability of advanced detector hardware and calibration equipment/ services, either by centralized service providers or by portable transfer standards.

Future measurement and calibration needs for emerging technologies may not be covered by existing calibrations, such as calibrating devices with near 100% efficiency, detector arrays, detectors integrated into on-chip photonic systems, photon-number-resolving devices, picosecond-scale low-jitter devices, quantum-specific needs (e.g., full detector tomography), and extreme wavelength (e.g., UV, mid-IR) devices.

Finally, of a very practical nature, decreasing fiber-channel losses (from source, through application, to detector) would benefit all parties. For example, there is need for a cryogenic-compatible fiber-to-fiber connector with losses below fusion splice losses (<1 % loss in small-core fibers). Achieving this goal would require specialized tooling to provide fiber core-offset correction for each connector. Such development would likely also lead to lower fiber-to-detector and source-to-fiber losses.

B. Sources



*Examples of single-photon sources. (*Reprinted courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States)*

Source technology is lagging detector technology in the private sector. This is a consequence of a history of robust federal investments in private-sector detector technologies as compared to sources, and more importantly, the applications of single-photon detectors beyond quantum information, in other words, in classical optical technologies, as noted above. Because detector technology has a longer history of use in classical applications, it is not surprising that characterization tools for single-photon sources are not as well developed as those for detectors. This means that most vendors and customers are building their own source characterization tools and, as a consequence, measurement results often differ from one setup to another, even with the same source. Vendors and end users would benefit from a set of best practices and from a better understanding of the limitations of characterization tools. Also, source specialization makes it more challenging to achieve consensus on a comprehensive set of measurable parameters, and at times the simultaneous measurement of certain performance metrics is desired. All of these factors make source characterization challenging for vendors and end users alike.

The single-photon source industry is plagued by poor communication between vendors and potential customers. One manifestation is a poor understanding of customer needs on the part of vendors and a concomitant lack of awareness of vendor capabilities on the part of potential customers. Many customers, especially those new to quantum information, have a poor understanding of the nuances of quantum light sources and, in particular, the trade-offs among source metrics [1]. This lack of understanding is exacerbated by (and partially caused by) inconsistency of measurement techniques and the reporting of source metrics from one vendor to another, making it difficult for customers to make direct comparisons. The confusion around source metrics is symptomatic of the larger issue of poorly defined terminology within the single-photon community, a widely recognized problem.

Hardware challenges also remain. The prevalence of "home-built" characterization tools has led to measurement techniques with variability in both precision and accuracy. The community would benefit from a standard set of characterization tools or, short of that, a better understanding of how to incorporate measurement-device-specific shortcomings into source specifications. This is especially true when a characterization tool is used outside its design envelope, for example, extending to different wavelengths at which component performance may suffer. Ultimately, the goal should be to develop SI-traceable tools and techniques. The development path may be short for certain types of tools, for example, a calibrated detector for measuring source output rates.

However, many of the tools that are used to characterize quantum light sources are complex, involving many different components. For example, joint spectrum measurements or polarization state tomography will necessarily have longer development timelines. In addition, many quantum metrology challenges still require a substantial amount of research. These include, for example, characterization of large-scale entanglement, measures of the indistinguishability of photons, generation efficiencies, and spectral characterization.

C. Applications

Because applications in the quantum realm of single-photon technologies are just starting to emerge, applications are still too immature to point to clear and general solutions to the metrology challenges that exist, as each application has a unique set of measurement requirements. Nevertheless, some common solutions may exist. Quantum integrated photonics relies on on-chip routing of single photons. While a chip with only a few components may still be characterizable, scaling up this technology to millions of components will require in-situ or on-chip characterization tools. These tools do not exist, and research and development could be done, for example, to make standard cells within an integrated circuit that serve as probes and measurement systems for sub-circuits of the whole chip. Also, validated design and simulation tools as they exist for standard microelectronics designs do not exist yet for photonic chips. Measurements and reproducibility studies could be performed such that full circuit simulations may be possible.

As is the case for sources and detectors, there is a need for standard definitions for integrated devices and best measurement practices. Metrics include cross-device pump leakage, optical crosstalk, electrical crosstalk, and thermal crosstalk. It was determined that such a standardization will aid the development of measurement tools and metrology for integrated devices and provide a self-consistent framework for training users and vendors through common language. These standards can also pertain to using standard analysis packages such that data will be analyzed according to the same protocols.

A few vendors/suppliers of application components expressed their concern that the high cost of measurement tools is a considerable challenge and suggested initiating a route to share or rent expensive measurement equipment. In addition, a pool of skilled labor to use the state-of-the-art measurement tools is highly desired, in other words, a complete rental measurement solution, which could be provided by NIST or third-party organizations with staff devoted to these types of hard measurements.

Lastly, space communication applications and quantum networks will require continuous in-situ measurements informing the control plane on the most efficient and transparent photon transport. Future measurement suites capable of probing parts of the (space) quantum network will provide continuous valuable telemetry data to the network control plane. The measurement suites will consist of the classical and quantum resources.

D. Summary

Although it became apparent that the field was too immature to prepare a detailed metrology roadmap with specific performance characteristics and timelines, there were several recurring themes that emerged during the workshop. These themes reflected existing and near-term anticipated needs of many of the participants. We have consolidated those themes into four focus areas: (1) information, (2) people, (3) components, and (4) services. The following section highlights the recommendations for actions and funding within those themes.

4. Recommendations

The workshop yielded valuable input and many promising ideas about how to improve single-photon characterization infrastructure and leverage existing capabilities to advance economic interests related to quantum information. Although the workshop was organized according to technology function (detectors, sources, applications), many of the recommendations from participants cut across these categories and were found to be broadly relevant. It was further determined that the ideas emerging from the community could be grouped into four focus areas: information, people, components, and services. The issues and gaps related to these four focus areas are discussed in greater detail below; and several specific recommendations are provided in priority order for each focus area. These recommendations are not intended to be prescriptive in terms of how they are to be implemented or supported. Rather, the intent is to bring the issues and gaps to the forefront and to motivate a path (or multiple paths) forward.

A. Information

Issues/Gaps. Lack of a clear and common understanding of single-photon metrics was noted both between vendors and users and within the vendor community. This was a recurring theme throughout the workshop, and this issue applied to both source and detector technologies. The issue involves documentation that may be incomplete due to lack of access to specialized and costly equipment, lack of best practice guidance and training [1], and perhaps staff resources to develop the needed in-house expertise.

Proposed Resolutions. Several actionable items were suggested to address these needs.

1. *Documented best practices and/or "application notes."* The best approach would facilitate community-sourced content curated by (and perhaps sponsored by) an organization such as QED-C. Note that this proposed resolution is highly supported by proposed resolution 2, below.
2. *Development of a common dictionary of relevant terms.* An effort to create such a dictionary is underway at NIST, with drafts currently being circulated.
3. *Well-documented software tools that can be easily used by the community for device and system performance characterization*. Examples of such tools are the NIST software packages to extract correlations from a time-tagged series data set to extract deadtime and afterpulsing characteristics [3] and to analyze mode structure of single-photon sources [4]. (We also note a need for validated software-design tools, but this is beyond the metrology focus of this document).

B. People

Issues/Gaps. The rapid growth of quantum information is attracting new students, customers, employees, and companies to the community. One of the themes that emerged from the workshop is that, although quantum information development is driven by pockets of deep expertise, there is a knowledge deficit across large parts of the community. Regarding metrology, this deficit is evident at many different levels and among all types of constituents: many customers lack knowledge of the nuances of the trade-offs among various performance metrics; vendors often develop their own characterization tools that may not be consistent with best practices; students often emerge from universities lacking expertise outside their niche specialties; and leading metrology R&D is not informed by vendor needs.

Proposed Resolutions. Improved communication among stakeholders will help remedy many of the issues described above. Some specific actions to help facilitate better communication include:

1. *Educational material to address common questions and misconceptions among consumers of quantum technologies.* This material might take the form of documents and videos. The impact can be maximized through active outreach.
2. *Metrology training sessions to provide vendors with the latest characterization techniques.* This activity, which would likely be led by NIST staff, could also serve to improve communication among vendors.
3. *Embedded researcher programs at NIST or other government laboratories and targeted toward QED-C members.* The goals would be two-fold: (1) enable vendor technical staff to develop deeper metrology expertise and (2) help identify metrology needs that could be addressed by NIST (or other laboratories).
4. *Student intern program with centralized pre-training session.* The goal would be to equip students with a baseline set of skills relevant to commercial developers, with an emphasis on diversity and inclusion.

C. Components

Issues/Gaps. Emerging and existing quantum applications have driven the development of novel, high-performance sources and detectors. However, it was identified that as systems scale up and "proof-of-principle" demonstrations progress into common adoption, there will be an increasing need for significantly improved performance from supporting system components and ways to document performance measurements. There is no standardized set of parts and measurement tools that can be easily purchased and trusted to be of highest, or even adequate, performance for quantum applications. Reliable, repeatable, and available quality components—such as laser sources, fiber connectors, attenuators, and power meters—are needed.

Proposed Resolutions. Although there are likely specialized needs for each application, there was general agreement that improvements to certain components would benefit the entire community. Such improved components would enable vendors to perform calibrations and state reliable metrics; enable end users to verify these metrics; and ultimately enable the resulting systems using these components to achieve the required system performance in quantum applications.

1) *Development of stable, broadband, portable/disseminable single-photon-level calibration sources and detectors with well-defined and documented performance characteristics.* This proposed resolution can overlap significantly with Services proposed resolution number 1, below.
2) *Development of robust means to routinely perform cryogenic-compatible small-core fiber-to-fiber connections* with losses below 1%, with even better performance (e.g., <0.2%) for room-temperature connections. This includes temporary/reusable fiber connectors and splicing hardware/programs/knowledge to achieve ultra-low-loss fiber splicing.
3) *Research to improve fiber-to-device or fiber-to-chip coupling methods.* Over time, as system sizes increase and systems are pushed to significant integration, on- and off-chip coupling will increase in importance. This effort is critical to extending a low-loss robust infrastructure into larger systems such as quantum networks.

D. Services

Issues/Gaps. The practical difficulties that manufacturers and users face when trying to make accurate measurements at the component and system level emerged as a theme during the workshop. These difficulties included both a lack of expertise and difficulty gaining access to the often specialized and expensive equipment needed to make state-of-the-art measurements. Moving equipment to different locations for calibrations or intercomparisons is difficult. The alternative of using third-party assessments of products on the market—using consistent metrics and clearly defined equipment—is also lacking.

Proposed Resolutions. Many of these problems can be addressed by developing services that are supported by, or provided by, national metrology institutions (NMIs). These government-supported labs can act as an unbiased repository for both expert personnel and for physical standards and equipment.

1) *Development of physical standards and transfer standards at NMIs that can be loaned or sold to the user and utilized at the user's site for calibrations.* This would partially address the difficulty in obtaining direct access to specialized equipment while also contending with a lack of expertise. Some specific examples include calibrated trap detectors for use as transfer standards, calibrated single-photon sources, and calibrated attenuator sets. Ideally these types of tools would be available at multiple wavelengths of interest, not just the telecommunications wavelength.
2) *Development of traditional calibration services at NMIs for single-photon applications.* It is expected that these services will provide the lowest levels of uncertainty of all approaches. Examples of specific needs mentioned are quantifying detector efficiencies above 98% and complete spectral characterization, although many other metrics were also identified. It was noted that definitions must be settled in tandem with the development of calibration services.
3) *Creation of a 'user' lab operated by QED-C and/or its members, or by NIST.* An additional consideration would be low-cost or government-funded equipment loans to users. This would help to improve access to advanced technologies (and expertise), which helps the entire industry and removes barriers for small businesses. Potential users envisioned a lab to which they could bring their own devices that would have knowledgeable staff and state-of-the-art equipment available for supervised use. This might include multiple brands of cryostats, calibrated single-photon detectors, sources, and transfer standards for multiple laser wavelengths, and high-quality test equipment. NIST and the Department of Defense (DOD) already have the Calibration Coordination Group (CCG) in place, which could be a possible avenue to expand service directly to DOD metrology labs.
4) *Development of third-party certifications/measurements beyond NMI calibration services.* While such services might not reach the uncertainty levels provided by an NMI service, they could be cheaper. This is another way to address the need for unbiased third-party assessments.

5. Conclusions

Several urgent needs and priorities have been identified that, if adequately addressed, will help to facilitate a more robust and self-sustaining market for high-quality single-photon technologies that meet the needs of the quantum industry. We note that the themes and gaps highlighted in this report echo those that were identified in other QED-C reports: information, people, components, and services.

It is clear that single-photon metrology and broader associated measurement technologies must be further developed to facilitate the economic viability of the emerging quantum industry in computing, networking, and sensing. Therefore, this report provides recommendations for actions within the identified focus areas to enable the commercial sector to take full advantage of metrology resources currently available and to take part in and make use of future development of the metrology and measurement training infrastructure. A follow-up reassessment of technology needs in the future is recommended to probe the readiness of the community to develop a concrete roadmap.

This report serves as a resource for QED-C members and U.S. government agencies to guide research and development priorities and investments for single-photon technologies. Some of the needs may be addressed by government or individual companies independently. Others will benefit from leveraged partnerships, collaborations, and other approaches to speed progress. QED-C is organized to support areas of research that members feel can benefit from a collaborative approach and the government sees as vital to the goals of the National Quantum Initiative.

6. References

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[2] QED-C. "Cryogenic Advances a Must for Quantum Technology Applications." 12 July 2021. https://quantumconsortium.org/blog/cryogenic-advances-a-must-for-quantum-technology-applications/.

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Appendix A. Workshop agenda

Session 1: Tuesday, September 14, 2021 **Detectors** **Chair: Jack Berg**	
Goal of session: Generate discussion about measurement needs for single-photon detectors to assess the state of the art in detector characterization and to identify gaps in measurement capabilities with performance targets.	
12:00 pm - 12:15 pm	• Welcome and brief introduction **- Jack Berg, PsiQuantum** ○ Goal of the workshop: report/roadmap that describes low-level optical quantum measurement infrastructure needs/gaps with performance targets ○ Agenda for today's session ○ Guidelines for participant involvement
12:15 pm - 12:40 pm	Single Photon Applications Overview – 20+5 min Saikat Guha, University of Arizona
12:40 pm - 12:55 pm	• Detector Technology Overview - 12+3 min Properties and measurements of advanced single-photon detectors, **Karl Berggren, Massachusetts Institute of Technology**
12:55 pm – 1:35 pm	• Detector characterization • 8+2 minutes each; What can be measured? What is most important to measure? ○ Practical challenges to achieving reliable single-photon detector calibrations **Aaron Miller, Quantum Opus** ○ Measurement needs for the calibration of SNSPD systems **Vikas Anant, PhotonSpot** ○ An overview of single-photon detector calibration techniques **Angela Gamouras, National Research Council Canada** ○ Emerging challenges for SNSPD deployment and characterization: low timing jitter, photon-number resolution, and mid-infrared operation **Boris Korzh, Jet Propulsion Laboratory**
1:35 pm – 1:50 pm	• Detector Characterization, NIST perspective - 12+3min **SaeWoo Nam, NIST**
1:50 pm – 2:05 pm	• Break
2:05 pm – 2:15 pm	• Directions for guided discussion during breakout session
2:15 pm – 3:05 pm	• Breakout sessions 50 min
3:05 pm – 3:50 pm	• Breakout session summary, full group discussion 45 min
3:50 pm - 4:00 pm	• Adjourn
4:00 pm – 4:30 pm	• Optional informal, virtual happy hour

Session 2: Wednesday, September 15, 2021 **Sources** **Chair: Warren Grice**	
Goal of session: Generate discussion about measurement needs for single-photon sources to assess the state of the art in source characterization and to identify gaps in measurement capabilities with performance targets.	
12:00 pm – 12:15 pm	● Welcome ○ Goal of the workshop: report/roadmap that describes low-level optical quantum measurement infrastructure needs/gaps with performance targets ○ Agenda for today's session ○ Guidelines for participant involvement
12:15 pm – 12:30 pm	● Source technology Overview - 12+3mins. **Paul Kwiat, University of Illinois Urbana-Champaign**
12:30 pm – 1:20 pm	● Source characterization ● 8+2 minutes each; What can be measured? What is most important to measure? ○ Molecule-based single photon source for quantum radiometry **Stefan Kück, PTB** ○ Measuring entangled photon sources **Greg Kanter, NuCrypt** Industry perspective and needs on entangled photon sources **Duncan Earl, Qubitekk** ○ Emerging single-photon emitter technologies **Val Zwiller, KTH** ○ Scalable photon sources in silicon and lithium niobate integrated photonics **Shayan Mookherjea, Univ. of California, San Diego**
1:20 pm – 1:35 pm	● Source characterization, NIST perspective - 12+3min **Krister Shalm, NIST**
1:35 pm – 1:50 pm	● Break
1:50 pm – 2:00 pm	● Directions for guided discussion during breakout session
2:00 pm – 3:00 pm	● Breakout sessions 60 min
3:00 pm – 3:45 pm	● Breakout session summary, full group discussion 45 min
3:45 pm - 4:00 pm	● Adjourn
4:00 pm – 4:30 pm	● Optional informal, virtual happy hour

Session 3: Monday, September 20, 2021 **Applications** **Chair: Prem Kumar**	
Goal of session: Generate discussion about measurement challenges related to system integrations, foundries, characterization, performance validation and identify gaps in measurement capabilities.	
12:00 pm – 12:15 pm	• Welcome ○ Goal of the workshop: report/roadmap that describes low-level optical quantum measurement infrastructure needs/gaps with performance targets ○ Agenda for today's session ○ Guidelines for participant involvement
12:15 pm – 1:45 pm	• Overview of specific applications • 8+2 minutes each; Focus on integration, characterization, foundries, and performance validation challenges ○ What standards are needed for QKD now? **Alan Mink, NIST** ○ Working toward a common language **Josh Bienfang, NIST** ○ Optical fiber power meter calibration at NIST **John Lehman, NIST** ○ Needs for fully integrated photonic quantum systems **Jack Berg, PsiQuantum** ○ Measurement gaps in integrated quantum photonics **Ryan Camacho, BYU** ○ PICs for Quantum **Wil Oxford, Anametric** ○ Quantum integrated photonics: heterogeneous integration of qubit technologies **Michael Fanto, USAF** ○ Integrated photonics and single-photon detectors for trapped-ion quantum information processing **John Chiaverini, MIT-LL** ○ Metrology for space-based quantum communication systems **Evan Katz, NASA Glenn Research Center**
1:45 pm – 2:00 pm	• Break
2:00 pm – 2:10 pm	• Directions for guided discussion during breakout session
2:10 pm – 3:00 pm	• Breakout sessions 50 min
3:00 pm – 3:50 pm	• Breakout session summary, full group discussion, 50 min
3:50 pm – 4:00 pm	• Adjourn
4:00 pm – 4:30 pm	• Optional informal, virtual happy hour

Session 4: Tuesday, September 21, 2021 **Summary and Roadmap Development** **Chair: Michelle Stephens**	
Goal of session: Solicit input from participants that will allow organizers to draft a workshop report/roadmap that describes low-level optical quantum measurement infrastructure needs/gaps with performance targets.	
12:00 pm – 12:15 pm	• Welcome ○ Goal of the workshop: report/roadmap that describes low-level optical quantum measurement infrastructure needs/gaps with performance targets ○ Agenda for today's session ○ Guidelines for participant involvement
12:15 pm – 12:30 pm	• Day 1 summary, 15 min, **Jack Berg**
12:30 pm – 12:45 pm	• Day 2 summary, 15 min, **Warren Grice**
12:45 pm – 1:00 pm	• Day 3 summary, 15 min, **Prem Kumar**
1:00 pm – 1:20 pm	• NIST priorities and a perspective, 17+3 min **Barbara Goldstein, NIST**
1:20 pm – 1:35 pm	• Break
1:35 pm – 1:50 pm	• Directions for breakout sessions • Success criteria: concrete quantum measurement needs with performance targets, time scale for development, identification of application measurement supports
1:50 pm – 2:50 pm	• Breakout sessions, 60 min • Three sessions: Sources, detectors, applications
2:50 - 3:45 pm	• Breakout session summary, full group discussion, 55 min
3:45 – 4:00 pm	• Final readout and wrap-up
4:00 - 4:30 pm	• Optional informal, virtual happy hour

Appendix B. Summary of pre-workshop survey

A pre-workshop survey was sent out to mailing lists of the primary contacts of QED-C members, the 2019 single-photon workshop attendees, and a mailing list provided by Rochester Institute of Technology. QED-C received 67 responses to bolster the presentations and discussions that would take place in the workshop. Survey questions aimed at identifying metrology gaps for single-photon technologies (detectors, sources, and applications). General questions helped identify the type of respondee (i.e., supplier, user, commercial, academia, and government). Specific questions addressed metrology-related topics aiming at identifying the current shortcomings of measurement capabilities to advance single-photon technologies.

The responses were approximately evenly distributed between academia, government, and industry (30%, 30%, and about 25%, respectively). Half of the respondents identified themselves as users, 36% as suppliers, and 14% as research and development.

The table below presents the utilized single-photon technology of users and suppliers in descending order of prevalence.

Detectors		**Sources**	
Users	**Suppliers**	**Users**	**Suppliers**
SPAD	SNSPD	SPDC	SPDC
SNSPD	SPAD	Integrated	Q-dots
TES	TES	Q-dots	Defect-based sources
EM-CCD	SiPM	Defect-based sources	Integrated
PMT	PMT	Ions	Trapped ions
CMOS		Atoms	Molecule-based
MKID		Attenuated lasers	

Note: See Appendix C for a list of acronyms.

Based on the feedback, the survey was able to identify the following most prominent characterization issues for detectors in descending order:

- Accurate measurements of detection efficiency
- Measurement of coupling losses to the detector
- Spectral responsivity characterization
- In-house validation
- Lack of standards
- Knowledge and evaluation of polarization dependent losses
- Well-traced uncertainties
- Single-photon detector jitter evaluation

Source characterization issues:

- Accurate evaluation of single-photon generation efficiencies
- Coupling from device to a specific output mode with low or well-known loss

- Spectral characterization of source output
- Reproducibility: multiple source statistics
- Lack of standards
- Well-traced uncertainties
- Characterization of photons to identify indistinguishability

Further, the survey identified these main measurement challenges over the next five years:

- Quantifying >98% efficiencies
- Standard procedures for testing and validating devices
- Reducing coupling losses (low-loss connections)
- Spectral response characterization

The survey focused on technology and metrology gaps, which were discussed and covered in depth during the workshop and in particular during the breakout sessions. Even though there was large diversity among the respondents (e.g., quantum optics, AMO, biology, astrophysics), there was broad agreement that the most important challenges are for quantification of efficiencies of sources and detectors and for understanding coupling losses. Other gaps that need to be filled are the lack of in-house validation tools and the lack of standardization for testing and measuring metrics. All focus areas (information, people, components, and services) were addressed in the survey and by the responses and helped shape the general focus areas for the workshop.

Appendix C. Acronym list

AMO	Atomic, Molecular, and Optical Physics
APD	Avalanche Photodiode
BYU	Brigham Young University
CCD	Charge-Coupled Device
CCG	Calibration Coordination Group
CMOS	Complementary Metal-Oxide Semiconductor
EM-CCD	Electron Multiplying CCD
KTH	Kungliga Tekniska högskolan (KTH Royal Institute of Technology)
IR	Infra-Red
MKID	Microwave Kinetic Inductance Detector
MIT-LL	Massachusetts Institute of Technology - Lincoln Laboratory
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NMI	National Metrology Institute
ORNL	Oak Ridge National Laboratory
PMT	Photomultiplier Tube
PTB	Physikalisch-Technische Bundesanstalt
QED-C	Quantum Economic Development Consortium
QKD	Quantum Key Distribution
R&D	Research and Development
RIT	Rochester Institute of Technology
SI	International System of Units
SiPM	Silicon Photomultiplier
SNSPD	Superconducting Nanowire Single-Photon Detectors
SPAD	Single Photon Avalanche Diode
SPDC	Spontaneous Parametric Down Conversion
SPMIQA	Single-Photon Measurement Infrastructure for Quantum Applications
TES	Transition Edge Sensor
USAF	United States Air Force
UV	Ultra-Violet