TRACKING THE GLOBAL SUPPLY CHAIN

A FRAMEWORK FOR THE QUANTUM INDUSTRY

August 2023

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Executive summary

Quantum information science and technology (QIST) represents an emerging area of technology development with potential for extraordinary impact on the global scientific, industrial, and strategic landscape. Its potential has created widespread public and private sector interest in the global quantum supply chain and the creation of better tools to assess its health. Consistent with this and broader national and economic security interests, the United States Air Force Research Laboratory requested that SRI develop a framework for tracking the global quantum supply chain (QSC).

To understand the range of potential use cases for a prospective quantum supply chain tracking tool, SRI conducted a series of interviews and workshops with stakeholders from several private and public sector organizations involved in the quantum ecosystem, including Quantum Economic Development Consortium (QED-C) member companies. To complement views on tool needs and use cases on the part of organizations involved in QIST, SRI examined the efforts to track industry supply chains outside of the quantum industry, including those in information and communications technology, pharmaceuticals, and space.

This evaluation highlighted four principles the project team adopted to guide framework development, in anticipation that the framework would be used to guide development of an eventual tracking tool:

- Principle 1: Create a supply chain tracking approach that can be implemented in a practical tool
- Principle 2: Launch an initial proof-of-concept tool and expand coverage and functionality over time
- Principle 3: Maintain confidence in data to support adoption
- Principle 4: Ensure data and tool security

The proposed framework organizes technology components and materials according to a view of the quantum stack, which includes key supply chain elements for quantum technologies such as computing, sensing and metrology, and telecommunications and networking. At its foundation, the proposed framework tracks the technology components and materials that make up the quantum stack and the entities that produce them. This *who-makes-what* use case was identified as a priority by virtually all the organizations with which SRI spoke.

Within the proposed framework, every component and material is associated with one or more entities. Each component and material may also be associated with one or more other components or materials. Supply chain tiers are captured via this connection from component-to-component or component-to-material. Companies are unwilling to share information on their customers and suppliers, so the framework does not require any tracking of entity-to-entity connections.

Given the scope and diversity of quantum technologies, the proposed framework prioritizes what is monitored in two key ways. First, SRI proposes including only a subset of the overall quantum supply chain, specifically, a subset of elements about which there is the greatest concern regarding supply. Second, for these important elements, the framework tracks only the most important upstream inputs.

Building a prospective supply chain tracking tool will require collecting a set of core data elements that includes:

- Firmographic data for entities

- The component and material associations data that link components and materials to entities
- Select technical performance data specific to each component and material
- Material-to-component and component-to-component connections

These core data are readily available and SRI expects much of it will come directly from entities supplying the components and materials used in the quantum supply chain. While firms will not share supplier and customer information, they are generally eager to provide information on their products and services. With the core data, a prospective quantum supply chain tracking tool could be used to address a range of questions, such as:

- For what components and materials is the U.S. supply chain dependent on non-U.S. sources?
- For what components and materials is the U.S. supply chain dependent on a single supplier?
- In what areas of the quantum supply chain should the U.S. government be investing in R&D?
- What U.S. suppliers currently provide key technologies?
- What share of suppliers for a given technology component or material are U.S.-based?

Given the modest level of maturity and significant level of technical diversity associated with the quantum industry, SRI recommends buildout of an initial proof-of-concept tracking tool developed for a subsection of the global supply chain and for the most important elements in that subsection, including core data for all tracked entities, components, and materials. Initial user experience with a proof-of-concept tool could then be used to guide future refinements to and expansion of the tool's capabilities, including the addition of new data elements. SRI expects that a range of complementary data will be added over time to facilitate supply chain risk assessment and other quantum supply chain analyses. Additional data are available from diverse sources, including international organizations, private third parties, and agencies and departments of the U.S. federal government.

To maximize tool usability and value, it should be implemented via a graph database layered under a graphical user interface that uses data visualization techniques to allow users to query the system. To maximize tool usability, these visualizations should not require users to write code. Rather, that functionality needs to be developed for the tool's interface.

Any effort to develop a quantum supply chain tracking tool based on the framework proposed in this report must accommodate the significant effort involved in collecting, verifying, aggregating, and updating the necessary data. Confidence in the tool and thus its long-term use will depend on the quality of its underlying data. SRI's discussions with organizations that have built tools similar to the one proposed for quantum technology make clear that creation of a valuable tool requires a dedicated and continual data collection and preparation effort.

Project background and imperative

Quantum information science and technology (QIST) represents an emerging area of technology development with potential for extraordinary impact on the global scientific, industrial, and strategic landscape. QIST-related research and development (R&D) is making rapid progress in the fields of quantum computing, quantum sensing and metrology, and quantum telecommunications. Catalyzed by these advances, an emerging quantum industry is taking shape. Early products are entering the market and companies are developing internal roadmaps for more complex systems, such as error-corrected quantum computers that may eventually outperform classical computers for some real-world applications. Realizing the full potential of quantum technology will require the development of novel materials, devices, structures, and systems that can eventually be manufactured at scale.

There is, accordingly, widespread public and private sector interest in the health of the global quantum supply chain and the creation of better tools to assess this health. Better tools for assessing the risks and vulnerabilities to the supply chain are needed in order to ensure the United States' ability to develop and maintain advantage in the global quantum landscape. Such a tool could be used by policymakers to assess the overall status of the U.S. quantum technology supply chain, by government R&D program managers to better understand where their investments would have the greatest impact, by quantum system developers to identify potential suppliers, and by quantum technology suppliers to assess the segments of the market they are focused on.

Current approaches for supply chain assessment rely almost entirely on point-in-time studies of the supply chain or its component elements. Unless specific policy or management questions are anticipated prior to a study's completion, they are unlikely to be addressed by such an approach. A tool is needed that allows for real-time flexible analysis of the global quantum supply chain supply chain as specific concerns arise. Consistent with this need and broader national and economic security interests, the United States Air Force Research Laboratory (AFRL) requested that SRI develop a framework for tracking the global quantum supply chain. The framework developed by SRI is described in this report and is intended to form the basis for a readily buildable, practical, and extensible supply chain tracking tool that can be used to address a wide range of supply chain management and policy questions.

The framework

The framework proposed in this report was informed by extensive assessment of user needs in the quantum industry and the experience of other high technology industries to create mechanisms for assessing industry-wide supply chains. These analyses were complemented with a review of available supply chain data in the quantum industry and an evaluation of the data architecture and user interface requirements necessary for the most flexible and valuable tool. Appendix 1 describes SRI's methodology for developing the proposed framework.

Framework principles

Discussions with organizations and individuals in government and the private sector involved in the quantum industry and with those in other science-intensive industries highlighted a number of challenges to building a valuable supply chain tracking tool. In response to these challenges, the framework design team formulated a set of design principles for the framework. The principles are meant to ensure that any eventual tool built using the framework as its basis is as valuable as possible to a broad prospective user community.

Principle 1: Create a supply chain tracking approach that can be implemented in a practical tool

SRI developed the quantum supply chain tracking framework to support creation of a practical supply chain tracking tool. A practical tool is one that can realistically be developed. It is clear from the experience of other industries that data availability is a key factor in developing a supply chain tracking tool, perhaps the most important factor. In addition to drawing on available data, the tool must be global in coverage. This means it must capture the important portions of the quantum supply chain regardless of where they are located.

Principle 2: Launch a proof-of-concept tool and expand coverage and functionality over time

The quantum industry is an emerging one that currently has considerable uncertainty regarding what technical breakthroughs will be made, what approaches will prove the most effective, and what products will achieve widespread market acceptance. In addition to being less mature, the quantum industry is technically diverse, representing a remarkably broad range of applications, approaches, and underlying technologies. The industry's primary applications are quantum computing, quantum sensing and metrology, and quantum telecommunications. Even within these individual domains, there is substantial variety of R&D paths being pursued. For example, quantum computing includes superconducting quantum computers, photonic quantum computers, neutral atom quantum computers, and trapped ion quantum computers, among other approaches.

Given the modest level of maturity and significant level of technical diversity associated with the quantum industry, a complete view of the industry's global supply chain would be enormously detailed. It would also not be necessary for assessing key risks and opportunities, as certain elements of the global quantum supply chain are much more important than others and in much greater need of tracking. The most effective way to gain user input is from their reaction to an actual product. While diverse input on end-user needs for a supply chain tracking tool was collected for this project, these views are not comprehensive. Accordingly, SRI recommends the buildout of an initial tool that is a proof-of-concept. A proof-of-concept tool can be developed for a subsection of the global supply chain and for the most important elements in that subsection. Initial user experience with a proof-of-concept tool will guide ongoing refinements to the tool's capabilities and coverage over time. Launching with a proof-of-concept tool whose functionality is refined via feedback from actual use will allow the tool development team to expand coverage over time with respect to elements of the global supply chain covered and the type and detail of data included, facilitating its extensibility. This will be important, as SRI expects data collection and integration will represent the largest share of tool-building effort.

Common across virtually all the organizations spoken to is an urgent need to know what entities produce what items in the supply chain (items are either technology components or materials), where these entities are located, and who owns and controls these entities. Beyond provider and location interest, views varied regarding what additional information would be useful to include in a prospective supply chain tracking tool.

Principle 3: Maintain confidence in data to support adoption

Confidence in the supply chain tracking tool's underlying data will be essential for use. A documented, repeatable, and stable process will be required to collect and manage all tool data. There is a role for a centralized data collection organization to steward this process, regardless of the data sources. The data will also need to be updated with sufficient frequency to maintain ongoing policy relevance. In the near term, there will be considerable fluidity in the composition of the global quantum supply chain. These industry changes will need to be reflected in regular updates to the underlying data.

Principle 4: Ensure data and tool security

Consolidating a large amount of quantum industry supply chain data into one database, even when those data are publicly available, will create an asset of national strategic importance. Such data could, in principle, be used to identify weaknesses in the U.S. quantum supply chain or in other ways detrimental to U.S. national security or commercial strength. The data will need to be secured and access to the data and any associated supply chain tracking tool will need to be restricted.

Framework structure

At its foundation, the proposed framework tracks the technology components and materials in the global quantum supply chain and the entities that produce them, as illustrated in Figure 1. Technology components are represented in Figure 1 by dark blue rectangles; materials are represented by light blue rounded rectangles; entities are represented by green hexagons. Every component and material is associated with one or more entities. For example, in Figure 1, Component C8888 is associated with three supplier entities, E111, E222, and E333.

Each component and material may be associated with one or more other components or materials. Supply chain tiers are captured via this connection from component-to-component or component-to-material. Companies are almost universally unwilling to share information on their customers and suppliers, so the framework does not require any tracking of entity-to-entity connections. The three entities shown in Figure 1 are presented as suppliers of component C8888, with no relationship between these entities implied in the figure.

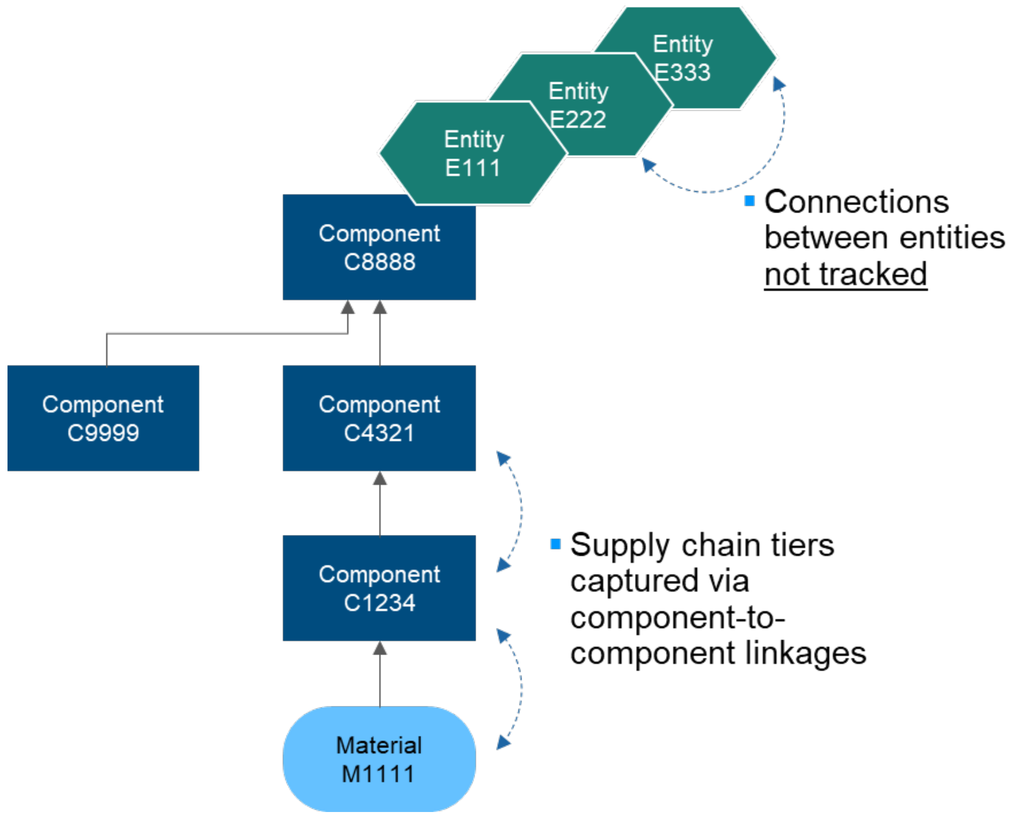

Figure 1: Quantum Supply Chain Tracking Framework

Figure 2 illustrates the proposed framework for the case of dilution refrigerators.[1] Five suppliers are identified for refrigerators. Upstream, four additional components and two materials are identified as inputs to refrigerators. Not shown in Figure 2 are the entity connections to each of these additional components and materials (pulse tube coolers, helium compressors, $HoCu_2$ spheres, helium compressor capsules, holmium, and helium-3). The proposed framework would track entity associations for all components and materials, including upstream elements such as those shown in Figure 2. They are hidden here to keep the visual uncluttered.

[1] The components and materials shown in this example were identified by Luke Mauritsen for a case study of supply chain tracking that was prepared for the QED-C report, *Toward a Resilient Quantum Computing Supply Chain: Response to the American COMPETE Act*, April 2022.

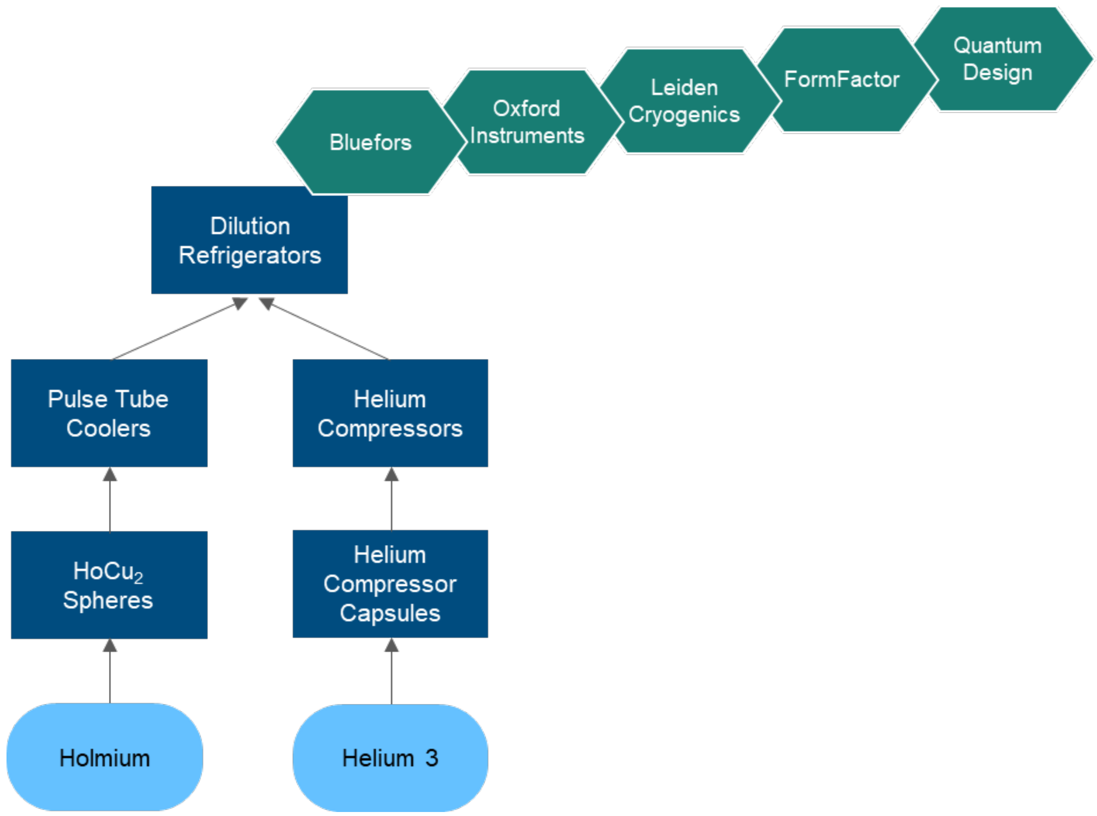

Figure 2: Quantum Supply Chain Tracking Framework, Dilution Refrigerator Example

Framework supply chain coverage

The proposed quantum supply chain framework organizes technology components and materials according to a view of the quantum stack that includes key supply chain elements for quantum computing, quantum sensing and metrology, and quantum telecommunications and networking. Figure 3 provides a preliminary view of the quantum stack, organized by category. Within the proposed framework, each of the technology components and materials listed in Figure 3 would be tracked per the structure of Figure 1. That is to say, every component and material is associated with one or more entities; and each component and material may be associated with one or more other components or materials, depending on the actual connections between those elements in manufacturing supply chains. The proposed framework would track all of these component and material associations.

The detail provided in Figure 3 is not exhaustive. It reflects a view of the most important elements of the quantum stack, i.e., those whose sourcing and origin is most in need of tracking. Figures 2 and 3 highlight an important design consideration for the framework, namely that it is not comprehensive in its coverage. It is prioritized in two key ways:

- The coverage of components and materials in the supply chain is not comprehensive (i.e., Figure 3 is not comprehensive)
- The upstream input components and materials for any tracked components may not be comprehensive (i.e., Figure 2 is not comprehensive)

An exhaustive list of the technology components and materials required to develop and manufacture quantum systems for end users would be enormous. It would also include a large number of items that are not the focus of concern among industry or policymakers. The preliminary list of components and materials in the stack shown in Figure 3 reflects the items of greatest concern—concern that results from their importance to quantum system R&D and manufacturing, their limited or uncertain supply, or their supply from geopolitically challenging parts of the world.

In a manner similar to how the quantum stack of Figure 3 is not comprehensive, the upstream supply chain illustrated for dilution refrigerators in Figure 2 does not reflect a complete bill of materials for a dilution refrigerator. Companies and policymakers are unlikely to be concerned with all the items of the bill of materials for a given piece of technology, so not all the items would merit inclusion in a prospective quantum supply chain tracking tool. Radiation shielding, for example, though important to dilution refrigerator operation, is typically made from gold-plated copper, two materials readily available in the U.S. and not important to track.

The framework of Figure 1 allows for straightforward additions of new elements within the global quantum supply chain. In this manner, it provides the basis for a supply chain tracking tool that is fundamentally extensible; it can be extended to include any new components or materials as those materials become important and as interest in tracking them becomes more widespread.

Component Classification	Component Categories	Components
Non-Quantum Components	Network Technology	Protocols, specialty cladding fiber, etc.
	Software and Correction Technology	Software and firmware for controlling quantum hardware necessary for quantum products
	Control Technology	Cryogenics CMOS, SFQ, control electronics, stabilized lasers, latest CMOS technology, etc.
	Interface Components	SNSPDs, QLAs, cryoLNAs, cryoRF, HD connectors and wiring, I/O, detector arrays, lasers, ion taps, AOMs, etc.
	Environmental Technology	Cryocoolers, compressors, dilution refrigerators, sorption coolers, AORs, UHV chambers, thermometry, etc.
Quantum Components & Materials	Quantum Devices	Qubits (superconducting, ion, atom, defect, quantum dot, photonic, etc.), transducers, memory, sensors, entangled sources, etc.
	Quantum Materials	Rare earths, two dimensional materials, superconducting materials, non-linear photonics, thin films, micro-fabricated materials

Figure 3: Quantum Stack Listing Tracked Components and Materials

Framework data and data sources

The proposed framework makes use of a variety of data categories pertaining to entities, components, and materials.

Entity data

Figure 4 summarizes the data categories proposed for entities. The first category includes firmographic data identifying such characteristics such as where suppliers are based, what industry segments they participate in, and who owns them. SRI expects entity firmographic data to come primarily from entity self-reporting. As needed, these data can be sourced from regulatory filings and from commercial third-party data sources that provide company information, such as PitchBook, Bloomberg, and Crunchbase

Included in commercial data providers is The Quantum Insider, a market intelligence firm focused exclusively on the quantum industry. The Quantum Insider has worked with SRI previously, including providing input on the quantum computing supply chain resiliency assessment included in QED-C’s 2022 response to the American COMPETE Act.[2]

Although data are available from regulatory filings and third parties, all data for a specific data element would ideally come from the same source. QED-C members consulted during the need assessment phase of this project indicated they would be willing to provide firmographic data and product data. Accordingly, core entity data collection should target collecting as much core entity data as possible directly from entities.

Data Categories	Data Description	Expected Data Sources
Firmographics	Primary entity information such as type, location, ownership, industry classification, etc.	• Entity self-reporting • Regulatory filings • Commercial third parties
Assessment Data	Wide range of entity attributes that can be used to assess status and risks, including legal standing in the U.S., geopolitical risk, business risk, economic risk, etc.	• Variety of sources, pending focus • Emphasis on U.S. government data sources
Classified Data	Possible classified information regarding entities, including classified tags	• Classified sources
Component and Material Associations	Tags linking entities to the components and materials they produce	• Entity self-reporting

Figure 4: Quantum Supply Chain Entity Data

In addition to firmographic data, SRI proposes that a range of other entity-specific data be added over time to a prospective supply chain tracking tool to enhance its usefulness. These data may be tied directly to the entities themselves or may be connected to entity characteristics such as industry classification or location, as identified by country of headquarters, country of operation, or country of ownership and industry classification. These data can be used to assess such factors as the market risk, business risk, or geopolitical risk associated with a particular entity and with the components and materials it supplies.

The sources for this type of data are numerous. International organizations provide standardized cross-country comparisons on economic and risk conditions. For example, the United Nations provides country-level Ease of Doing Business scores. Private third parties provide extensive data on country risk, such as the data available from Moody's, Standard & Poor's, and the Economist Intelligence Unit.

Agencies and departments of the U.S. federal government also provide country-level assessment data.

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[2] *Toward a Resilient Quantum Computing Supply Chain: Response to the American COMPETE Act*, April 2022.

Much of this information is qualitative in nature and not readily included in supply chain tracking data, but some of it is in a form that can be easily analyzed. For example, the U.S. Department of Commerce maintains a list of parties of concern, entities for which U.S. entities should perform additional due diligence when considering partnerships. This information could be easily accommodated in entity data as country-of-concern flags.

The final category of framework entity data is the component and materials associations for each entity. The associations identify what entities provide which components and materials. In principle, the manner in which these associations are made within the data will depend on how a prospective quantum supply chain tracking tool is implemented. For example, if the data are stored as a relational database, entity data, component data, and material data would be stored in three separate data tables. A separate connective hierarchy table would be used to link these tables via unique identifiers included for each entity, component, and material record. Alternatively, the data may be stored in a graph database for which the relationship stored between each record indicates the associations between entities, components, and materials. In order to maximize the usefulness of a prospective supply chain tracking tool, SRI recommends implementing such tool via a graph database layered under a graphical user interface that uses data visualization techniques. See the discussion of the *Interface design and user functionality* section below.

The firmographic and the component and material associations data make up what in the framework is designated *core* entity data. Core data are those SRI considers necessary for the launch of a proof-of-concept supply chain tracking tool.

Component and material data

Core component and material data will include:

- Entity associations for each component and material
- Select technical performance data specific to each component and material, such as wavelength, power, and temperature

Technical performance data will, of course, vary by component and material and be prioritized on each supply chain element's most important metric or metrics. SRI expects core component and material data to come primarily from the entities that produce them. In most cases, this information is publicly available, and QED-C members consulted during the need assessment phase of the project indicated they would be willing to provide additional information of this type as needed to ensure complete and accurate data capture. Although firms are not willing to provide information on their own suppliers, they did indicate a willingness to provide information on who the principal suppliers are for a given technology component or material. For select specialized elements of the supply chain for which there is little public commercial information, this indirect source of supplier information may be important.

As with the entity data, SRI would expect to append additional data to the core component and material data to enhance the usefulness of a prospective supply chain tracking tool. Export control-related data represent one important source of external data. Compliance with export control regulation can be burdensome, especially for smaller manufacturers. Export-controlled technologies are governed by the U.S. Department of State International Traffic in Arms Regulations (ITAR) or the U.S. Department of Commerce Export Administration Regulations (EAR). Items regulated by ITAR are placed on the U.S. Munitions List (USML). The EAR regime controls items and technologies considered to be dual use and places controlled technologies on the Commerce Control List (CCL). Smaller firms would benefit from the presence of a flag in the component and material databases indicating technologies' inclusion on either of these lists.

The perspectives provided by potential users of a prospective supply chain tracking tool make clear their primary short-term interest in knowing:

- Which entities provide the technologies and materials that are essential for quantum system research, development, and manufacturing
- What risks or other supply challenges are associated with acquiring needed inputs from these entities
- For what components and materials are individual quantum system developers and manufacturers most dependent on problematic supply sources
- For what components and materials is the United States most dependent on problematic supply sources

SRI recommends that an initial buildout of a proof-of-concept supply chain tracking tool focus on these central analytic considerations. Over time, as tool users gain experience with an initial tool, informed decisions can be made about what new data would be most valuable to add. As with coverage of tracked elements, the framework's inherent extensibility will support additions to the tracking tool at the entity, component, and material levels.

Scale of production data

Much of the technology in the quantum supply chain is not yet mature. Some components are available at what is often referred to as R&D scale but not at the higher volumes needed for large scale manufacturing. Input from prospective users of a future supply chain tracking tool indicates that knowing the scale at which components can be provided would be valuable.

The primary source identified for this information is component manufacturers. Manufacturers may overstate the capabilities of their products. Several QED-C members indicated that their experience as technology users could provide validation of manufacturer-provided scale information. This perspective was shared by a relatively small number of firms, and it is not known what share of technology users would be willing to provide this information given firms' well-established declination to disclose supplier data of any kind. Determining the extent to which scale and availability data can be included in a prospective supply chain tracking tool will require more extensive interaction with manufacturers in the context of building out an initial proof-of-concept tool.

Classified data

In discussing use cases with potential government users of a prospective supply chain tracking tool, some government staff members mentioned the possibility of adding classified data to the database. Classified data elements are most likely to be associated with entities and entity location, though in principle, such data could be relevant to components and materials as well.

Any classified data will be employed privately by the government agencies that hold the data in question, in compliance with federal and agency-specific regulations regarding classified data use. The proposed framework allows for use of the supply chain tracking tool data offline so that it can be integrated with users' in-house proprietary data, including classified data.

Interface design and user functionality

The ideal data structure to represent a global supply chain is dependent on how pieces of the supply chain relate to one another. In the quantum supply chain, materials are processed into components, which in turn are assembled into more complex components and subassemblies for inclusion in quantum equipment; components do not become raw materials and subassemblies do not become components. This directionality and the nature of relationships between materials, components, and entities mean that, together, the data on materials, components, and suppliers comprise a directed graph. The one-way relationships are captured abstractly in a directed graph in which each entity is a node and the relationships between materials, components, and suppliers are the edges.

The data structures leveraged for this framework will need to reflect the relationship-based nature of the supply chain data and store not only the attributes of all elements, but also the connections between them. There are multiple possible implementation strategies for storing these data that can preserve the informational content of each node and the relationship content of each edge, each with its own advantages and drawbacks with respect to the proposed framework.

Traditional relational databases are effective at capturing entity features and providing fast, reliable methods for conducting calculations on these features, but they do not have strong support for preserving relationship data where multiple nodes connect to each other to form chains between upstream inputs and downstream outputs. It is difficult to preserve sequence-based information when a variable number of sequential connections exist, as is the case with any manufacturing supply flow. The data architecture must be able to represent a sequence where there is just one component between the raw material and the final manufactured item equally as well as sequences with multiple tiers of assembly between the raw material and the final manufactured item. A relational database would be an effective data structure if all sequences had a standardized or maximum length but not where there is variation in depth of tiers.

A second implementation option is a commercial dashboarding technology, such as Tableau or Power BI, that allows complex hierarchical data to be visualized such that users can drill down to view data on elements within the supply chain with increasingly lower-level views of the data. These tools allow users to begin at any point in the directed graph connecting materials to suppliers through components and to then identify the earlier components and materials required to manufacture the element in question. Further selection from within these elements would allow deeper investigation into subcomponents and materials. These tools are easy to maintain and update, provide simplified user interaction without the need to write code, and provide strong data tools for midsize datasets that are smaller than big data but too big or complex for conventional data tools, such as spreadsheets.

Commercial dashboarding platforms have similar limitations as relational databases in that they store data in a way that does not capture their full directed graph structure. Accordingly, they are not able to flexibly show variable-length sequences without additional user interactions, such as clicking to drill down. Existing data visualization tools could provide some of the desired information connecting materials, components, and suppliers, but the overall functionality would be inherently limited due to the way existing dashboarding tools require data to be stored.

The highest fidelity representation of these data would be a graph database layered under a graphical user interface that uses data visualization techniques to allow users to query the system. Such a system would be able to accurately reflect relational information showing the steps between upstream and downstream components because its implemented structure would mirror the abstract structure of the data themselves. Because graph databases are typically unfamiliar to most users and therefore have a higher barrier to effective use and querying, SRI recommends pairing this data storage method with a front-end user tool for interaction that does not require the use of code.

Such a user tool would feature a graph explorer to display nodes of materials, components, and entities with arrows linking the selected node to items with which that node has a relationship. For example, selecting a component would show the materials and subcomponents required for that component, arrows to the quantum machines that use that component, and the entities that produce that component. The data for the tool would be stored in the cloud and accessible to users over the web. The tool would also feature a data download function to allow for additional local analysis of data presented in the graph explorer, facilitating integration of the tool's data with users' own proprietary data. SRI recommends this graph database with a custom front-end implementation as the most flexible and useful method for storing and visualizing the supply chain data.

Prospective analysis

Identifying manufacturer-to-manufacturer production chains for specific elements of the quantum supply chain, from raw materials through final assembly, is not possible without access to company supply data from a large share of the industry. The proposed framework in Figure 1 overcomes the absence of such data and facilitates the widest possible supply chain analyses. It enables supply chain assessment analyses regarding what entities provide which technologies and components, and by extension, from what geographies components and materials are sourced.

The following questions are representative of those raised by quantum system developers and policymakers during the during the need assessment phase of this project:

- For what components and materials is the U.S. supply chain dependent on non-U.S. sources?
- For what components and materials is the U.S. supply chain dependent on overseas sources considered allies or strategic partners?
- For what components and materials is the U.S. supply chain dependent on a single source of supply?
- In what areas of the quantum supply chain should the U.S. government be investing in R&D?
- What U.S. suppliers currently provide key technologies?
- What share of suppliers for a given technology component or material are U.S.-based?
- What markets that are adjacent to a manufacturer's existing technologies indicate significant unmet demand from current suppliers?

Each of these questions can be addressed with the proposed framework using only those data elements identified as core data. Supplementing core data with readily available additional information will allow an even wider set of supply chain assessment questions to be addressed, such as:

- For what components and materials is the U.S. supply chain dependent on sources located in countries subject to significant geopolitical risk?
- What components and materials are subject to U.S. export controls?
- What share of suppliers for a given technology component or material are sourced from at-risk suppliers?

The range of questions addressable with a supply chain tracking tool based on the proposed framework is as diverse as the supply chain concerns of the tool's potential user base. As long as relevant data can be identified and acquired, virtually any entity-, component-, or material-related analyses can be accommodated by the proposed framework. Adding relevant data will require only a critical mass of interest on the part of tracking tool users.

Recommendations and next steps

The framework described in this report is intended to support buildout of a practical and extensible supply chain tracking tool. If a tool is to be developed, SRI recommends developing a proof-of-concept tool based on the proposed framework for a set of components similar to the stack of Figure 3 and including core entity, component, and material data, per Figure 5.

Entity Data	Technology Component Data	Material Data	Component and Material Graph Connections
• Entity type • Entity headquarters location • Component associations • Material associations	• Entity associations for each component • Select technical performance data (component specific)	• Entity associations for each material • Select technical performance data (material specific)	• Upstream component and material connections for each component

Figure 5: Core Framework Data

The entities SRI spoke to while gathering insight on potential use cases for a supply chain tracking tool were nearly unanimous in their desire to see such a tool built. Strong interest was shared by private sector and public sector organizations alike. Though a detailed workplan for building an initial proof-of-concept tool depends on timing, scope, and budget, SRI has identified several key next steps in the creation of a proof-of-concept tracking tool.

Prioritization of the quantum stack

The quantum stack presented in Figure 3 reflects general agreement on the most important elements in the quantum supply chain and those most in need of systematic tracking. Agreement does not imply consensus regarding what parts of the global quantum supply chain are most in need of tracking and assessment. True consensus is not practical to achieve given the diversity of interests in the industry and the relative immaturity of its technologies. For example, the QED-C Laser Prioritization Tool includes detailed technical specifications for 131 laser configurations, differentiated by gain medium, wavelength, linewidth, and optical power. Including 131 lasers in a supply chain tracking tool, at least at launch, is not practical. The lasers included in a launch version of a prospective tracking tool will need to be prioritized beyond the prioritization highlighted in Figure 3. This is true for all the components and materials that would be tracked in a prospective supply chain tracking tool. Though, defining the list of elements to be tracked at the micro level is beyond the scope of this framework development project, fully prioritizing the list of tracked components and materials included in a proof-of-concept supply chain tracking tool represents one of the primary areas of work to develop the tool.

Prioritization of tracked elements

A next step closely related to refining the stack of Figure 3 is to prioritize the upstream components and materials for each element of the stack. A proof-of-concept tool will not track all components and materials associated with the elements included in the quantum stack, but will focus on elements of greatest interest to users. The list of prioritized components and materials will need to be developed in concert with potential users in a manner similar to the refinement of the stack.

Data collection and integration

Tables 1 through 4 identify the primary sources of data for use in a prospective proof-of-concept tracking tool. Core data for entities are shown in Tables 1 and core data for components are shown in the first 6 rows of Table 3. All of the material data shown in Table 4 are core data. Supplementary (i.e., non-core) data for entities that can be readily added to a prospective supply chain tracking tool are described in Table 2.

SRI expects two complementary data sourcing models for the prospective tracking tool. Some of the data will come from regulators and commercial third-parties; other data will come from entities that provide the components and materials needed for quantum system development. While some entity data will be available from company websites, product information sheets, news releases, and other publicly available company documentation, SRI expects that the tool development team will need to interact directly with companies to collect the most complete and accurate information regarding components and materials. This will be especially true in establishing the technical performance parameters for components and materials. SRI expects that entities will also provide essential information on the upstream components and materials input for each tracked component.

In the case of externally supplied information, the tool development team will need to verify, organize, and integrate the data. Third party data are often not made available in the form needed to support specific use cases and need to be refined before use. This conversion effort will likely require significant and ongoing effort.

Technical implementation

SRI recommends that any initial supply chain tracking tool be developed as a proof-of-concept. Extensive input was gathered from potential tool users during the course of this project and this insight was used to develop the supply chain tracking framework, including likely initial data sources, the optimal database structure, and user interface needs. Developing a proof-of-concept tracking tool will allow the tool development team to refine the tool's functioning and capabilities in response to actual user experience. Future versions of the tool may expand coverage and data inclusion based on early experience from initial users. Some data elements in addition to the provider and location core are discussed in this report, but final decisions are left as a next step. SRI expects three areas of expansion in response to users' evolving priorities:

- Tracking of more items in the quantum stack
- Tracking a larger number of upstream technology components and materials associated with each item in the quantum stack
- Integration of more data sources for use in the quantum supply chain assessment

Expanding tool coverage will be critical given the rapid pace at which quantum technology is evolving and ever-shifting interests within the industry and with global supply conditions. Driving tool expansion based on actual user experience and user needs will ensure the effort required for expansion has the highest possible return.

As described in the *Interface design and user functionality* section, the highest fidelity representation of the data associated with a supply chain tracking tool would be a graph database layered under a graphical user interface that uses data visualization techniques to allow users to query the system. To maximize tool usability, these visualizations should not require users to write code. Rather, that functionality needs to be developed for the tool's interface. Interface functionality are part of a complete set of functional requirements that would need to be determined, including user requirements, system requirements, and overall interface requirements. Non-functional requirements regarding performance, reliability, usability, security, scalability, and maintainability would also need to be created as an early next step in tool development.

Among the important functional requirements for the tool is the updating frequency for data. Data will need to be updated annually. The ideal frequency of updates will likely vary by type and data source. For some data elements, SRI expects that data will need to be updated more frequently than annually.

Data and tool stewardship

Any effort to develop a supply chain tracking tool based on the framework proposed in this report must accommodate the significant effort involved in collecting, verifying, aggregating, and updating the necessary data. Confidence in the tool and thus its long-term use will depend on the quality of its underlying data. SRI's discussions with organizations that have built tools similar to the one proposed for quantum technology make clear that creation of a valuable tool requires a large and dedicated data collection and preparation effort. Even in the case of the Satellite Applications Catapult in the UK that relies extensively on regulator data not available in the U.S.,[3] and even after the tool was launched, the Catapult team expends considerable, ongoing effort to maintain the tool's data. This level of effort on the order of $1M per year will be needed for a quantum supply chain tracking tool, both to create the original tool and to keep data updated.

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[3] The Catapult tool relies extensively on regulatory data made available by Companies House, the executive agency of the British Government that maintains the government's register of companies that includes all forms of companies in the United Kingdom, regardless of ownership, including private companies. The U.S. Security and Exchange Commission, Companies House's U.S. equivalent, requires regulatory reporting largely from public companies only and therefore only provides data on a small share of U.S. companies.

Appendix 1: Methodology

Development of this framework was driven by an extensive assessment of user need, complemented with a review of available data and an evaluation of the data architecture and user interface requirements necessary for the most flexible and valuable tool. To understand the range of potential use cases for a supply chain tracking tool, SRI collected perspectives from public and private sector organizations through roundtables and interviews. Government organizations consulted include:

- Office of the Undersecretary of Defense for Research and Engineering (OUSD (R&E))
- Air Force Concepts, Development Management (CDM) Office of Commercial & Economic Analysis (OCEA)
- Air Force Research Laboratory (AFRL)
- U.S. Government Accountability Office (GAO)
- Idaho National Laboratory
- International Trade Administration (U.S. Department of Commerce)
- National Telecommunications and Information Administration (U.S. Department of Commerce)
- National Quantum Initiative Advisory Committee (NQIAC)[4]
- Naval Quantum Computing Office (QCPO)

SRI collected input on potential supply chain tracking tool use cases directly from QED-C members at two in-person sessions held during the June 2023 QED-C plenary meeting and during the July 2023 QED-C Steering Committee meeting. To complement these views of supply chain tracking tool needs and use cases on the part of organizations involved in QIST, SRI examined efforts to track industry supply chains outside of the quantum ecosystem, including:

- Information and communications technology—The Alliance for Telecommunications Industry Solutions (ATIS)
- Pharmaceuticals—Pistoia Alliance
- Space—Satellite Applications Catapult[5]

These perspectives informed the quantum supply chain tracking tool framework.

SRI reviewed data available from public sources and commercial third parties, beyond the data expected to be gathered directly from suppliers. A wide range of data are available from public and commercial sources that bear on supply chain status and risk assessment. These sources include market intelligence firms that focus exclusively on the quantum industry (e.g., The Quantum Insider). Appendix 2 describes initial data sources for a prospective quantum supply chain tracking tool.

In parallel to addressing data availability, SRI assessed options for database architecture and the user interface of a prospective supply chain tracking tool. Tradeoffs in architecture approaches and user interface options were assessed against expected uses of the tool, including uses that might require

[4] Interview with Luke Mauritsen, founder of Montana Instruments and former member of the NQIAC.
[5] Satellite Applications Catapult is one of nine catapult entities created as part of the Innovate UK program in the United Kingdom. The program provides a range of services intended to help bridge the gap between research and industry.

downloading the quantum supply chain database for integration with proprietary or classified data.[6]

[6] Local here refers to use of the quantum supply chain tracking tool and associated data at an end user site.

Appendix 2: Data Elements and Sources for the Prospective Tool

Data Element	Data Type	Description	Data Source(s)
Entity Name	Text	Legal name of the entity	Entities
Entity ID	Numerical	Unique identifier created for use in this database. This entity ID will be used in the database to connect components to the entity.	Tool development team
Headquarters Location: City/State	Text	City where the entity is headquartered (a State as well if the entity is within the U.S.)	Entities; U.S. Securities and Exchange Commission; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Headquarters Location: Country	Text	Country where the entity is headquartered	Entities; U.S. Securities and Exchange Commission; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Industry Classification	Text	Industrial category of the entity	Entities; U.S. Securities and Exchange Commission
Ownership Status	Text	Whether the entity is privately held or public	Entities; PitchBook; Bloomberg; The Quantum Insider; Crunchbase

Table 1: Core Entity Data

Data Element	Data Type	Description	Data Source(s)
Country Risk	Flag	Assessment of the risk of the country the entity is headquartered in using data from private third parties	Moody's; Standard & Poor's; Economist Intelligence Unit
Sanction	Flag	The U.S. Department of the Treasury maintains lists of entities and individuals officially sanctioned by the U.S. Government.	U.S. Department of the Treasury
Lists of Parties of Concern	Flag	The Bureau of Industry and Security within the U.S. Department of Commerce maintains lists of parties of concern. The lists contain individuals and entities that the U.S. Government has flagged as being of concern. The interactions a U.S. business can do with a listed entity depend on the list the entity is on.	Bureau of Industry and Security within the U.S. Department of Commerce
FCC Covered List	Flag	The U.S. Federal Communications Commission (FCC) maintains a Covered List with prohibited equipment produced by specific entities.	U.S. Federal Communications Commission
Website	Text	Website of the entity	Entities
Year Founded	Numerical	Founding year of the entity	Entities; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Number of Employees	Numerical	Number of individuals employed by the entity	Entities; U.S. Securities and Exchange Commission; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Parent Company	Text	Any parent company if the entity is a subsidiary	Entities; U.S. Securities and Exchange Commission; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Active Patents	Numerical	Number of active patents the entity possesses	Entities; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
Sales	Numerical	Yearly sales figures of the entity	Entities; U.S. Securities and Exchange Commission; PitchBook; Bloomberg; The Quantum Insider; Crunchbase
External Investors	Text	List of any external investors of the entity	Entities; PitchBook; Bloomberg; The Quantum Insider; Crunchbase

Table 2: Non-Core Entity Data

Data Element	Data Type	Description	Data Source(s)
Component Name	Text	Common name for the component	Taxonomy established by tool development team
Component ID	Numerical	Unique identifier created for use in this database	Tool development team
Component Category	Text	Whether the component is hardware, software, applications systems, etc.	Entities
Model	Text	Name the entity uses for the component	Entities
Component Specifications	Text/Numerical	This will include several fields and provide specification of the listed component.	Entities
Component-Entity Association (Entity ID)	Numerical	ID of the entity that produces the component	Entities; third party data such as that from The Quantum Insider, refined by tool development team
Upstream Component and Material Connections	Text	Graph connections showing tracked components and materials used as inputs to the listed component	Entities, The Quantum Insider
Downstream Component Connections	Text	Graph connections showing tracked components which use the listed component as input	Entities, The Quantum Insider
USML Listing	Flag	The U.S. Department of State maintains the United States Munitions List (USML). This is a list of items designated as defense and space related by the U.S. Government.	U.S. Department of State and Code of Federal Regulations
CCL Listing	Flag	Bureau of Industry and Security maintains the Commerce Control List (CCL). The list includes items subject to export licensing authority of the Bureau of Industry and Security.	Bureau of Industry and Security within the U.S. Department of Commerce and Code of Federal Regulations
Country of Origin Restrictions	Flag	Some countries restrict the use of technologies exported to prevent that technology from being used for military purposes.	World Trade Organization

Table 3: Component Data

Data Element	Data Type	Description	Data Source(s)
Material Name	Text	Common name of the material	Taxonomy established by tool development team
Material ID	Text	Unique identifier created for use in this database	Tool development team
Material Specifications	Text	This will include several fields and provide specification of the listed material	Entities
Material-Entity Association (Entity ID)	Numerical	ID of the entity that produces the material	Third party data such as that from The Quantum Insider, refined by tool development team
Downstream Component Connections	Text	Graph connections showing tracked components which use the listed material as input	Entities, The Quantum Insider

Table 4: Materials Data

Acknowledgments

SRI staff are grateful to the QED-C member organizations and individuals who shared their perspectives during the many interviews and workshops that informed this report. The following SRI staff contributed to this report:

- Jessica Avery, Krystal Bouverot, Jacob Gottlieb, Shay Moore, Lucien Randazzese, and Brandon Van Hoff, SRI International Center for Innovation Strategy and Policy
- Celia Merzbacher, QED-C Executive Director
- Jonathan Felbinger, QED-C Deputy Director