Research Report

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An Assessment of U.S.-Allied Nations' Industrial Bases in Quantum Technology

Annex

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About This Annex

Quantum technology is an emerging technology area that the U.S. government has identified as important for future U.S. economic prosperity and national security. This volume is an annex to a report that assesses the quantum industrial bases of several U.S.-allied nations that are major players in the development of this technology.[1] The main report begins with a global look at the quantum technology ecosystem and then does four deeper dives into the quantum industrial bases of Australia, the United Kingdom, Germany, and Japan. It concludes with recommendations for how the United States can promote strong ties with its allies in quantum technology research and development.

RAND National Security Research Division

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[1] Edward Parker, Richard Silberglitt, Daniel Gonzales, Natalia Henriquez Sanchez, Justin W. Lee, Lindsay Rand, Jon Schmid, Peter Dortmans, and Christopher A. Eusebi, *An Assessment of U.S.-Allied Nations' Industrial Bases in Quantum Technology*, RAND Corporation, RR-A2055-1, forthcoming. The main report is available at www.rand.org/t/RRA2055-1.

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Appendix A

Additional Findings

This appendix presents additional findings that are mentioned but not presented in the main body of this report.

Scientific Research

Australia

Tables A.1, A.2, and A.3 present the top publishing organizations for quantum computing, quantum communications, and quantum sensing research, respectively, in the Australian dataset. This dataset includes publications with at least one author from an organization based in Australia.[2]

Table A.1. Institutions Publishing Quantum Computing Research with Australian Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Sydney	Australia	201	1.00
University of New South Wales	Australia	197	0.68
University of Technology Sydney	Australia	149	0.74
Australian National University	Australia	132	0.73
University of Melbourne	Australia	125	0.54
University of Queensland	Australia	123	0.73
Macquarie University	Australia	112	0.59
Royal Melbourne Institute of Technology University	Australia	73	0.60
University of Western Australia	Australia	71	0.24
Chinese Acadent of Sciences	China	59	0.51
Swinburne University of Technology	Australia	58	0.36
University of Waterloo	Canada	45	0.46
Griffith University	Australia	38	0.39
Tsinghua University	China	37	0.29
National University of Singapore	Singapore	36	0.41
Keio University	Japan	32	0.48

[2] In Table A.1, the cutoff point for inclusion is 20 publications. In the tables and figures that follow, distinct cutoff points are used to ensure the presentation of an adequate sample of publishing organizations.

Organization	Country	Publications	Eigenvector Centrality
Purdue University	United States	29	0.18
Delft University of Technology	Netherlands	28	0.38
Monash University	Australia	28	0.32
Massachusetts Institute of Technology	United States	25	0.43
University of Bristol	UK	23	0.36
University of Oxford	UK	22	0.34
University of California, Santa Barbara	United States	20	0.39

NOTE: UK = United Kingdom.

Table A.2. Institutions Publishing Quantum Communications Research with Australian Coauthors

Organization	Country	Publications	Eigenvector Centrality
Australian National University	Australia	109	0.92
University of Queensland	Australia	108	0.72
University of Technology Sydney	Australia	103	0.44
Macquarie University	Australia	77	0.48
University of Sydney	Australia	72	0.48
University of New South Wales	Australia	85	0.28
Griffith University	Australia	53	0.35
National University of Singapore	Singapore	39	0.36
Swinburne University of Technology	Australia	33	0.16
University of Waterloo	Canada	32	0.64
Chinese Academy of Sciences	China	31	0.24
Southwest University	China	19	0.05
University of Melbourne	Australia	19	0.13
University of Oxford	UK	19	0.57
Polish Academy of Sciences	Poland	17	0.06
University of Cambridge	UK	17	0.22
University of Wollongong	Australia	17	0.03
Queensland University of Technology	Australia	16	0.09
Royal Melbourne Institute of Technology University	Australia	16	0.20
University of Science and Technology of China	China	16	0.31
Macau University of Science and Technology	Macao	15	0.04
Monash University	Australia	14	0.60
Perimeter Institute for Theoretical Physics	Canada	14	0.18
Southwest Jiaotong University	China	14	0.04
Tsinghua University	China	13	0.07
University of York	UK	13	0.51

Table A.3. Institutions Publishing Quantum Sensing Research with Australian Coauthors

Organization	Country	Publications	Eigenvector Centrality
Austtralian National University	Australia	67	1.00
University of Queensland	Australia	48	0.68
Macquarie University	Australia	41	0.54
University of Sydney	Australia	35	0.67
University of New South Wales	Australia	33	0.63
University of Melbourne	Australia	31	0.55
Griffith University	Australia	29	0.55
University of Technol Sydney	Australia	27	0.75
Royal Melbourne Institute of Technology University	Australia	22	0.57
Chinese Academy of Sciences	China	18	0.60
Monash University	Australia	18	0.32
University of Waterloo	Canada	13	0.54
University of Bristol	UK	12	0.61
University of Science and Technology of China	China	11	0.50
University of New Mexico	United States	10	0.30
Ulm University	Germany	10	0.54
University of Western Australia	Australia	9	0.15
Australian Research Council	Australia	8	0.34
Heriot Watt University	UK	8	0.33
Massachusetts Institute of Technology	United States	7	0.30
National Institutes for Quantum and Radiological Science and Technology	Japan	7	0.19
Swinburne University of Technol	Australia	7	0.34

UK

Tables A.4, A.5, and A.6 present the top publishing organizations for quantum computing, quantum communications, and quantum sensing research, respectively, in the UK dataset. This dataset includes publications with at least one author from an organization based in the UK.

Table A.4. Institutions Publishing Quantum Computing Research with UK Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Oxford	UK	416	1.00
University College London	UK	240	0.71
University of Cambridge	UK	192	0.54
University of Bristol	UK	186	0.51
Imperial College London	UK	131	0.46
University of Southampton	UK	116	0.53
National University of Singapore	Singapore	108	0.49
University of Nottingham	UK	87	0.36
University of Glasgow	UK	81	0.42
University of Sheffield	UK	80	0.27
University of York	UK	78	0.26
University of Edinburgh	UK	73	0.32
University of Strathclyde	UK	71	0.49
Heriot Watt University	UK	67	0.37
Queen's University Belfast	UK	55	0.24
University of Leeds	UK	53	0.24
University of Sussex	UK	53	0.27
University of St. Andrews	UK	51	0.27
University of Surrey	UK	49	0.28
University of Birmingham	UK	48	0.15

Table A.5. Institutions Publishing Quantum Communications Research with UK Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Oxford	UK	215	1.00
University of Bristol	UK	172	0.94
University of Cambridge	UK	172	0.58
University of York	UK	130	0.67
Heriot Watt University	UK	97	0.58
University of Southampton	UK	95	0.53
National University of Singapore	Singapore	81	0.63
University of Glasgow	UK	76	0.91
University of Nottingham	UK	74	0.44
Toshiba Research Europe Ltd.	Japan	72	0.21
University of Leeds	UK	68	0.22

Organization	Country	Publications	Eigenvector Centrality
University College London	UK	61	0.44
University of Strathclyde	UK	57	0.51
Queen’s UniversityBelfast	UK	55	0.45
Imperial College London	UK	52	0.39
Perimeter Institute for Theoretical Physics	Canada	44	0.36
University of St. Andrews	UK	43	0.22
Hungarian Academy of Sciences	Hungary	42	0.13
University of Sheffield	UK	42	0.49
University of Waterloo	Canada	42	0.67

Table A.6. Institutions Publishing Quantum Sensing Research with UK Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Nottingham	UK	78	0.42
University of Glasgow	UK	67	0.39
University of Oxford	UK	63	0.48
University of Sussex	UK	44	0.27
University of Cambridge	UK	41	0.32
University of Birmingham	UK	38	0.95
University College London	UK	37	0.25
University of Bristol	UK	35	0.21
Imperial College London	UK	33	0.26
Heriot Watt University	UK	31	0.19
University of Strathclyde	UK	27	0.43
National Physical Laboratory	UK	26	0.68
University of Leeds	UK	24	0.08
University of Sheffield	UK	21	0.13
University of York	UK	20	0.13
University of Southampton	UK	18	0.35
University of Ulm	Germany	18	0.81
National University of Singapore	Singapore	17	0.14
Consiglio Nazionale delle Ricerche	Italy	16	0.25
Istituto Nazionale di Fisica Nucleare	UK	16	0.65
University of Science and Technology of China	China	16	0.11

NOTE: The most central organization is Leibniz University in Germany (not shown).

Germany

Tables A.7, A.8, and A.9 present the top publishing organizations for quantum computing, quantum communications, and quantum sensing research, respectively, in the German dataset. This dataset includes publications with at least one author from an organization based in Germany.

Table A.7. Institutions Publishing Quantum Computing Research with German Coauthors

Organization	Country	Publications	Eigenvector Centrality
Max Planck Institute of Quantum Optics	Germany	180	0.95
Technical University of Munich	Germany	170	0.93
Rheinisch-Westfälische Technische Hochschule Aachen	Germany	151	0.59
University of Ulm	Germany	131	0.94
Forschungszentrum Jülich	Germany	130	0.63
Free University of Berlin	Germany	127	0.68
Karlsruhe Institute of Technology	Germany	126	0.56
University of Stuttgart	Germany	122	0.59
Leibniz University Hannover	Germany	118	0.68
Johannes Gutenberg University Mainz	Germany	80	0.55
University of Bremen	Germany	80	0.15
Ruhr-Universität Bochum	Germany	78	0.38
University of Innsbruck	Austria	75	0.78
Max Planck Institute for the Physics of Complex Systems	Germany	71	0.55
University of Wurzburg	Germany	68	0.43
Harvard University	United States	66	0.91
Technical University Darmstadt	Germany	66	0.50
Max Planck Institute for Science of Light	Germany	59	0.34
Ludwig Maximilian Univiversity of Munich	Germany	57	0.51

NOTE: In addition, two organizations tied at 54 publications (not shown). The most central organization in the network is the University of Oxford (not shown).

Table A.8. Institutions Publishing Quantum Communications Research with German Coauthors

Organization	Country	Publications	Eigenvector Centrality
Technical University of Munich	Germany	121	0.58
Max Planck Institute of Quantum Optics	Germany	119	0.96
Max Planck Institute for Science of Light	Germany	77	0.84
Leibniz University Hannover	Germany	65	0.93
Technical University Darmstadt	Germany	57	0.21

Organization	Country	Publications	Eigenvector Centrality
Max Planck Institute for Mathematics in the Sciences	Germany	53	0.07
University of Ulm	Germany	52	0.75
Technical University Berlin	Germany	50	0.21
University of Stuttgart	Germany	48	0.36
Capital Normal University	China	46	0.06
Austrian Academy of Sciences	Austria	45	0.87
Humboldt University of Berlin	Germany	44	0.35
Free University of Berlin	Germany	43	0.57
University of Erlangen Nürnberg	Germany	43	0.27
University of Siegen	Germany	43	0.33
University of Paderborn	Germany	42	0.24
University of Würzburg	Germany	41	0.28
Ruhr-Universität Bochum	Germany	37	0.24
Barcelona Institute for Science and Technology	Spain	35	0.80
Johannes Gutenberg Univ Mainz	Germany	34	0.21

NOTE: The most central organization in the network is the University of Glasgow (not shown).

Table A.9. Institutions Publishing Quantum Sensing Research with German Coauthors

Organization	Country	Publications[a]	Eigenvector Centrality
Leibniz University Hannover	Germany	93	1.00
University of Ulm	Germany	89	0.87
University of Stuttgart	Germany	49	0.34
Technical University of Munich	Germany	35	0.38
Humboldt University	Germany	34	0.74
Max Planck Institute for Science of Light	Germany	32	0.29
Max Planck Institute of Quantum Optics	Germany	24	0.35
Johannes Gutenberg University Mainz	Germany	23	0.25
Physikalisch-Technische Bundesanstalt	Germany	23	0.27
Ulm University	Germany	23	0.10
University of Science and Technology of China	China	21	0.18
Austtralian National University	Australia	20	0.17
Free University of Berlin	Germany	20	0.30
University of California, Berkeley	United States	20	0.61
University of Hamburg	Germany	20	0.44
Heidelberg University	Germany	19	0.13
University of Erlangen Nurnberg	Germany	19	0.12
Technical University Darmstadt	Germany	18	0.28

Organization	Country	Publications[a]	Eigenvector Centrality
University of Bremen	Germany	18	0.36
Leibniz-Institut für Höchstfrequenztechnik	Germany	17	0.18

Japan

Tables A.10, A.11, and A.12 present the top publishing organizations for quantum computing, quantum communications, and quantum sensing research, respectively, in the Japanese dataset. This dataset includes publications with at least one author from an organization based in Japan.

Table A.10. Institutions Publishing Quantum Computing Research with Japanese Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Tokyo	Japan	373	1.00
RIKEN	Japan	266	0.98
Kyoto University	Japan	189	0.66
Osaka University	Japan	158	0.60
Nippon Telegraph and Telephone Corporation	Japan	144	0.51
Tohoku University	Japan	140	0.67
Keio University	Japan	138	0.56
National Institute of Information and Communications Technology	Japan	135	0.54
Nagoya University	Japan	122	0.33
Tokyo Institute of Technology	Japan	118	0.45
Yokohama National University	Japan	113	0.21
University of Michigan	United States	105	0.51
National Institute of Advanced Industrial Science and Technology	Japan	68	0.42
Hokkaido University	Japan	65	0.28
Tokyo University of Science	Japan	50	0.25
National Institute for Materials Science	Japan	46	0.39
Japan Science and Technology Agency	Japan	45	0.29
Waseda University	Japan	45	0.31
Chinese Academy of Sciences	China	43	0.46

NOTE: In addition, three organiations tied at 42 publications (not shown).

Table A.11. Institutions Publishing Quantum Communications Research with Japanese Coauthors

Organization	Country	Publications	Eigenvector Centrality
National Institute of Information and Communications Technology	Japan	174	0.36
University of Tokyo	Japan	171	1.00
Nippon Telegraph and Telephone Corporation	Japan	111	0.35
Nagoya University	Japan	86	0.29
Osaka University	Japan	68	0.38
RIKEN	Japan	64	0.33
Kyoto University	Japan	58	0.28
National University Singapore	Singapore	38	0.23
Keio University	Japan	35	0.13
Kyushu University	Japan	33	0.09
University of Michigan	United States	32	0.64
Tohoku University	Japan	29	0.19
Hokkaido University	Japan	28	0.11
University of Electro-Communications	Japan	28	0.13
Tamagawa University	Japan	25	0.05
Tokyo Institute of Technology	Japan	24	0.13
Louisiana State University	United States	21	0.66
Tokyo University of Science	Japan	21	0.13

Table A.12. Institutions Publishing Quantum Sensing Research with Japanese Coauthors

Organization	Country	Publications	Eigenvector Centrality
University of Tokyo	Japan	61	1.00
National Institute of Advanced Industrial Science and Technology	Japan	43	0.27
RIKEN	Japan	41	0.37
Osaka University	Japan	29	0.19
National Institutes for Quantum Science and Technology	Japan	25	0.31
Nippon Telegraph and Telephone Corporation	Japan	25	0.15
Keio University	Japan	23	0.10
Tohoku University	Japan	23	0.39
Tokyo Institute of Technology	Japan	23	0.35
Nagoya University	Japan	20	0.16
University of Michigan	United States	20	0.23

Organization	Country	Publications	Eigenvector Centrality
National Institute of Information and Communications Technology	Japan	18	0.26
Kyoto University	Japan	17	0.15
University of Tsukuba	Japan	17	0.26
National Institute for Materials Science	Japan	15	0.20
Natl Inst Informat	Japan	11	0.08
Chinese Academy of Sciences	China	10	0.86
Japan Science and Technology Agency	Japan	9	0.13
Kindai University	Japan	9	0.03
University of Stuttgart	Japan	9	0.15

Industry Activity

Figures A.1 through A.4 reproduce the national research collaboration and funding diagrams in Figures 3.17, 3.22, 3.27, and 3.32, respectively, with a more granular coloring scheme that identifies the type of each entity in more detail than in the main report. The discussion in the main text of the report draws on these finer categorizations.

Figure A.1. Australian Quantum Funding and Collaboration Ecosystem

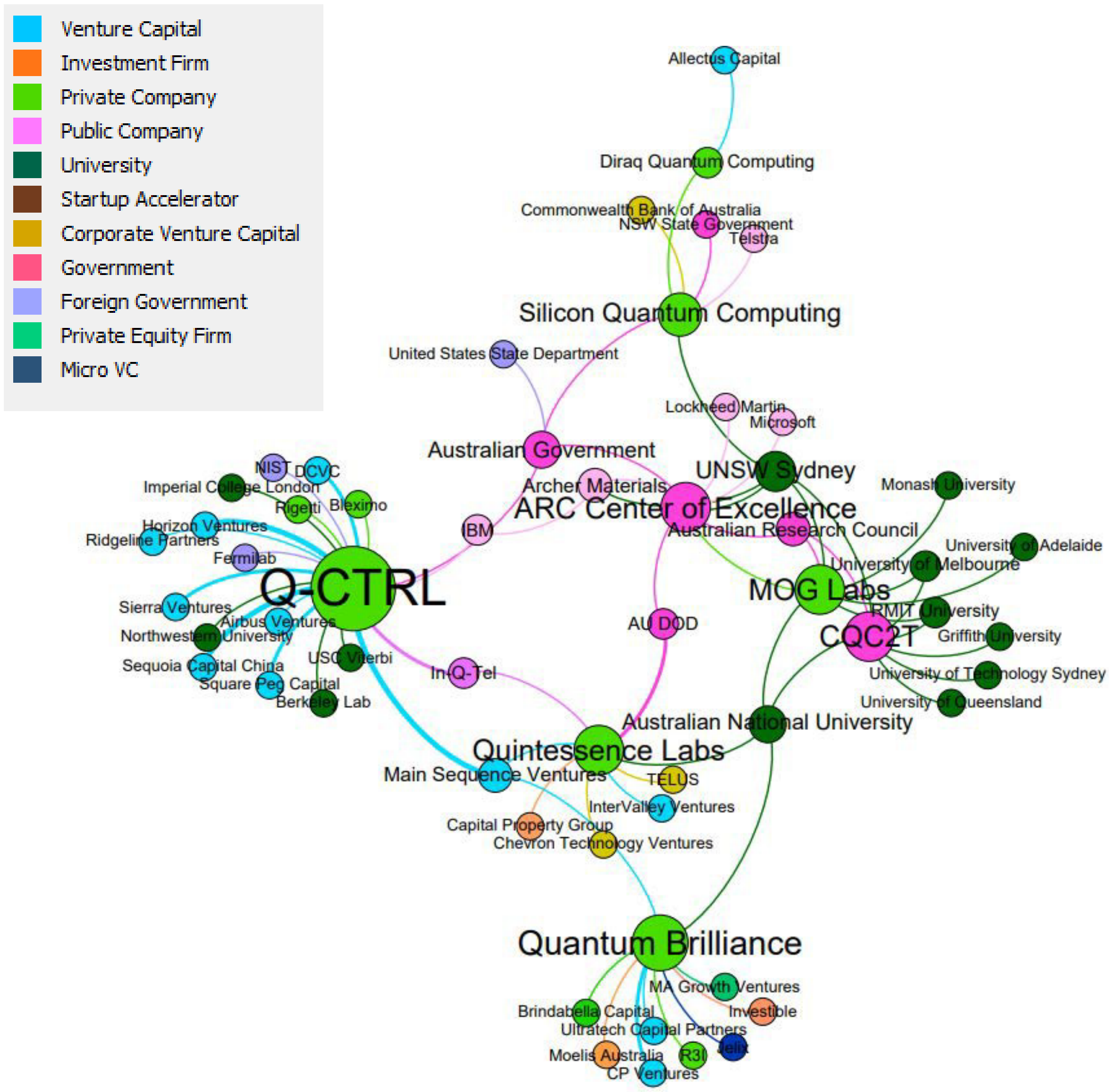


Figure A.2. UK Funding and Collaboration Ecosystem

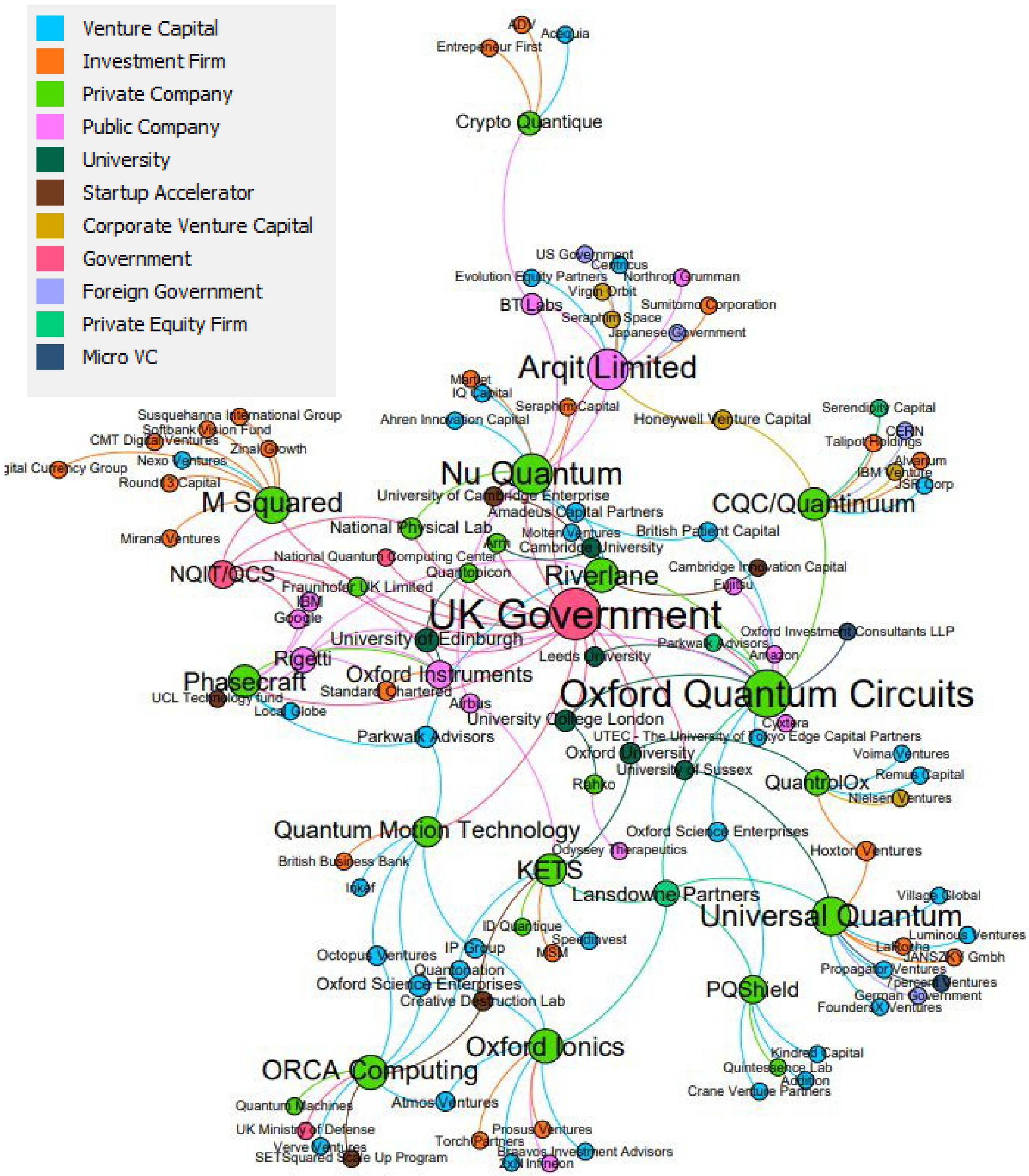


Figure A.3. German Funding and Collaboration Network

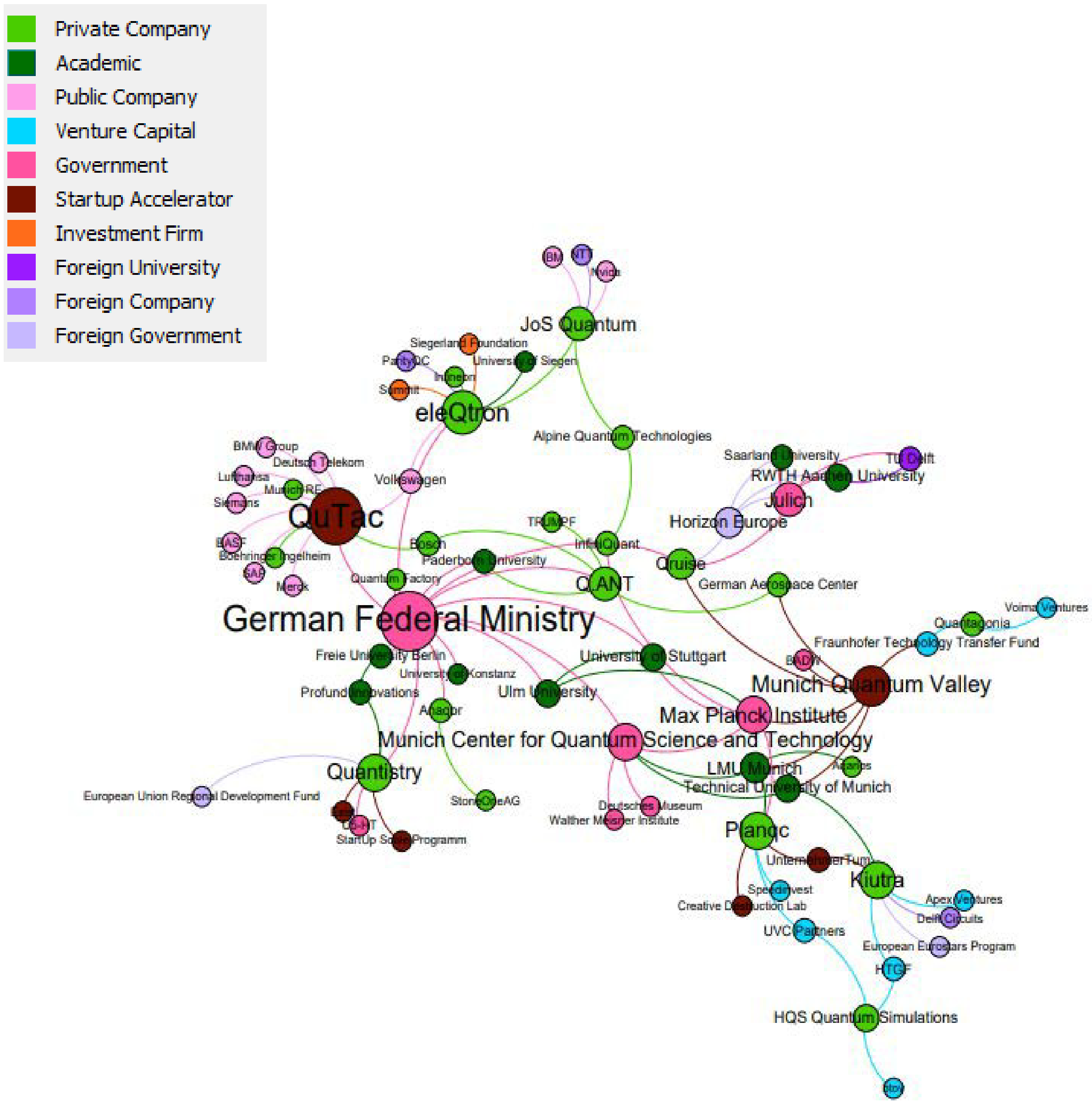
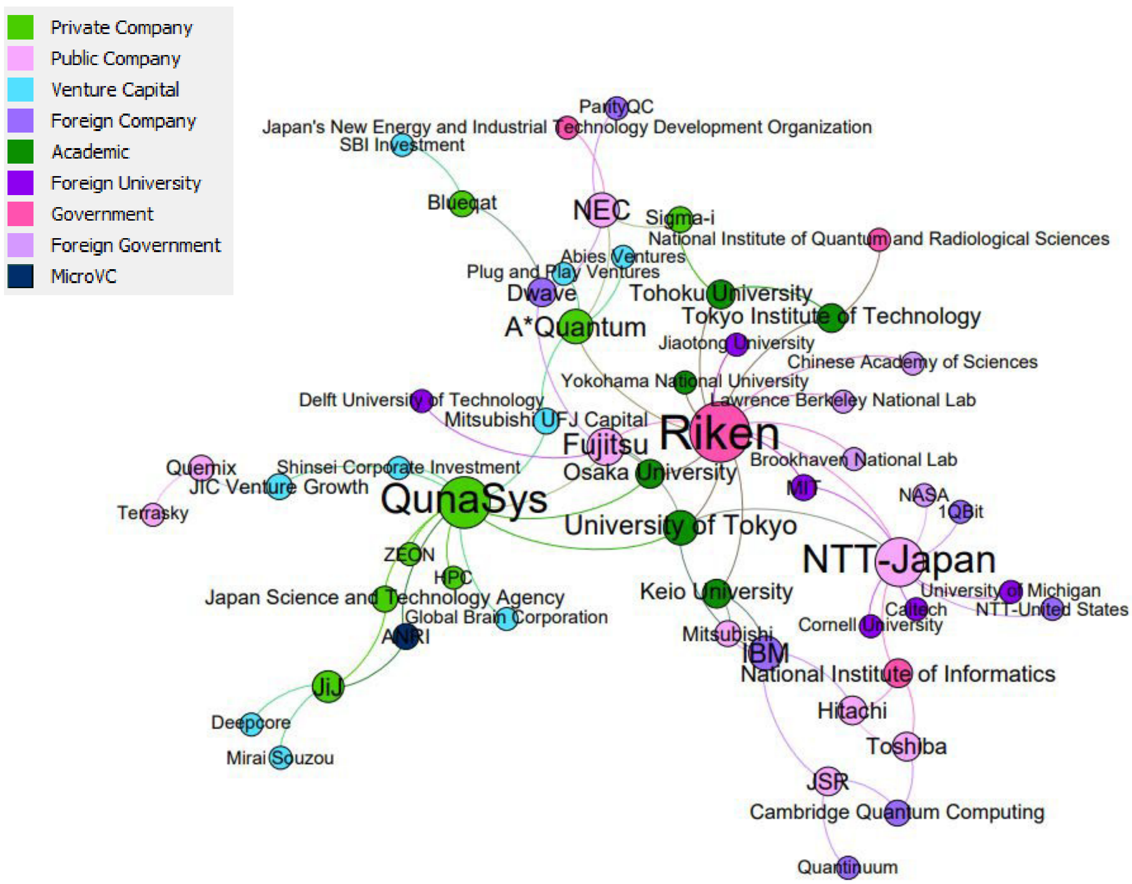


Figure A.4. Japan Quantum Funding and Collaboration Ecosystem



Technical Achievement

Areas of Global Patenting Apctivity

In addition to the cumulative patent counts, we investigated the technical areas in which patent applications have been filed in different countries in quantum computing, quantum communications, and quantum sensing. In this case, we included all countries filing patent applications. The technical areas were identical to those used for publications, which were defined by author-submitted keywords, as described previously.[3] Tables A.13 through A.18 show the number of patents and the percentage in each technical area for quantum computing, communications, and sensing, respectively. Each patent that included keywords representing a technical area was counted, so that patents containing multiple keywords were counted multiple times.

[3] Table B.1 lists these keywords. We selected the keywords from author-provided keywords from publications, not from patents. For consistency, we chose to use the same terms for both publications and patents to facilitate comparison. Unlike with the publications analysis, we could not start from databases of patents specific to the quantum technology application domains. Therefore, for each set of search terms, we counted only the patents that included the word *quantum* to attempt to restrict the search to patents on quantum information science and technology. The "quantum dot" category of terms still showed anomalously high counts (far higher than any other category), so within that category we counted only the patents that also included the word *qubit*. Nevertheless, the inclusion criteria for the patents may be less accurate than for the publications because we were not able to use the inclusion process described in Appendix B. The percentages reported in the Tables A.14, A.16, and A.18 are approximate and were produced by dividing (a) the number of patents from each country containing each keyword by (b) the total number of patents from that country containing any of the full set of keywords for that application domain. The former set is not necessarily a subset of the latter, but we believe that the percentages are still a useful baseline for comparison.

Table A.13. Patent Filings in Quantum Computing, by Technical Area

	USA	China	Japan	UK	South Korea	Austraila	Germany	Canada	France	Isreal	India	Finland	Italy	Netherlands	Russia	Sweden	Spain
Algorithms and end-user applications																	
Quantum simulation	4182	788	38	137	12	275	38	96	7	18	38	7	4	3	1	11	1
Quantum machine learning	265	324	44	16	55	17		2			5		5			4	
Optimization AND quantum	69	3	1								4						
Grover's algorithm	446	236	18	30	7	2	4	5	4	4	3		8		1	3	
Shor's algorithm	703	243	18	14	18	5	8	23	15		3		6	2	13	4	2
Variational quantum eigensolver	272	25	22	29	1	2	1	7	1						3		
QAOA	230	54	4	1		2		5	3		1						
Basic computational paradigms																	
Quantum annealing	1661	124	376	46	12	20	7	60	2	8	7	11					1
Cluster state	441	173	48	5	1		1	20	2	2					3		
adiabatic quantum computing	977	42	49	7	8	17	5	47			5	5					
boson sampling	53	9		5				4		1			2		2		5
noisy intermediate-scale quantum	271	111	18	18	4		1	4	3		3					6	
fault tolerant	4182	788	38	137	12	275	38	96	7	18	38	7	4	3	1	11	1
Hardware approaches																	
Optical computing	14488	1840	902	633	204	51	260	122	259	118	65	47	74	64	33	25	53
single-photon	6337	1001	255	334	116	38	145	41	28	99	21	79	22	6	36	16	23
Quantum dot	1033	66	28	73	4	74	37	16	24	14	1	1	2	11		1	
spin qubits	608	25	7	50		79	40	19	42		4	1		6			
Superconducting qubit	3882	504	81	59	21	42	11	79	19	1	4	15	1	13	1		4
Trapped ion	2107	167	23	92	12	16	1	59	13	3	7	1	2	5		3	
Rydberg atom	670	631	27	74	19	7	17	15	112	19	1	3	4	9	1	3	
nitrogen-vacancy center	357	107	98	8	7	9	66	4		15				8	1		
Majorana fermions	343	50	4	1			6	2	1	3						6	
Critical enablers, characterization, and benchmarking																	
Quantum error correction	1376	244	38	43	34	53	4	27	4	2	6		3	6		1	
Quantum control	920	547	149	11	15	49	14	25		12	8			1	1		
Fidelity AND Quantum																	
Quantum memory	3532	5145	388	103	128	27	50	10	27	5	6	7	6	6	4	11	1

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Table A.14. Percentage of Patent Filings in Quantum Computing, by Technical Area

	USA	China	Japan	UK	South Korea	Austraila	Germany	Canada	France	Isreal	India	Finland	Italy	Netherlands	Russia	Sweden	Spain
Algorithms and end-user applications																	
Quantum simulation	8%	6%	1%	7%	2%	26%	5%	12%	1%	5%	17%	4%	3%	2%	1%	10%	1%
Quantum machine learning	1%	2%	2%	1%	8%	2%	0%	0%	0%	0%	2%	0%	3%	0%	0%	4%	0%
Optimization AND quantum	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%
Grover's algorithm	1%	2%	1%	2%	1%	0%	1%	1%	1%	1%	1%	0%	6%	0%	1%	3%	0%
Shor's algorithm	1%	2%	1%	1%	3%	0%	1%	3%	3%	0%	1%	0%	4%	1%	13%	4%	2%
Variational quantum eigensolver	1%	0%	1%	2%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	3%	0%	0%
QAOA	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Basic computational paradigms																	
Quantum annealing	3%	1%	14%	2%	2%	2%	1%	8%	0%	2%	3%	6%	0%	0%	0%	0%	1%
Cluster state	1%	1%	2%	0%	0%	0%	0%	3%	0%	1%	0%	0%	0%	0%	3%	0%	0%
adiabatic quantum computing	2%	0%	2%	0%	1%	2%	1%	6%	0%	0%	2%	3%	0%	0%	0%	0%	0%
boson sampling	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	2%	0%	5%
noisy intermediate-scale quantum	1%	1%	1%	1%	1%	0%	0%	1%	1%	0%	1%	0%	0%	0%	0%	6%	0%
fault tolerant	8%	6%	1%	7%	2%	26%	5%	12%	1%	5%	17%	4%	3%	2%	1%	10%	1%
Hardware approaches																	
Optical computing	29%	14%	34%	33%	30%	5%	34%	15%	45%	35%	28%	26%	52%	45%	33%	24%	58%
single-photon	13%	8%	10%	17%	17%	4%	19%	5%	5%	29%	9%	43%	15%	4%	36%	15%	25%
Quantum dot	2%	0%	1%	4%	1%	7%	5%	2%	4%	4%	0%	1%	1%	8%	0%	1%	0%
spin qubits	1%	0%	0%	3%	0%	7%	5%	2%	7%	0%	2%	1%	0%	4%	0%	0%	0%
Superconducting qubit	8%	4%	3%	3%	3%	4%	1%	10%	3%	0%	2%	8%	1%	9%	1%	0%	4%
Trapped ion	4%	1%	1%	5%	2%	2%	0%	7%	2%	1%	3%	1%	1%	3%	0%	3%	0%
Rydberg atom	1%	5%	1%	4%	3%	1%	2%	2%	20%	6%	0%	2%	3%	6%	1%	3%	0%
nitrogen-vacancy center	1%	1%	4%	0%	1%	1%	9%	1%	0%	4%	0%	0%	0%	6%	1%	0%	0%
Majorana fermions	1%	0%	0%	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	6%	0%
Critical enablers, characterization, and benchmarking																	
Quantum error correction	3%	2%	1%	2%	5%	5%	1%	3%	1%	1%	3%	0%	2%	4%	0%	1%	0%
Quantum control	2%	4%	6%	1%	2%	5%	2%	3%	0%	4%	3%	0%	0%	1%	1%	0%	0%
Fidelity AND Quantum	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Quantum memory	7%	39%	15%	5%	19%	3%	7%	1%	5%	1%	3%	4%	4%	4%	4%	10%	1%
Total Quantum Sensing Patent Applications*	49405	13247	2674	1926	690	1060	754	788	573	342	230	184	143	143	101	105	91

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Table A.15. Patent Filings in Quantum Communications, by Technical Area

	USA	China	Japan	UK	South Korea	France	Germany	Canada	Australia	Italy	Israel	India	Malaysia	Poland	Singapore	Spain	Russia
Quantum-secured communication																	
Quantum cryptography	4252	2934	854	600	342	180	170	18	34	60	30	36	42	40	36	44	34
Quantum key distribution	3308	6948	686	740	364	74	60	48	60	44	34	16	124	24	36	62	22
Secure multiparty computation	164	52	2	14		2					2						
Entanglement-based protocols																	
entanglement swapping	174	180	10	40	2	20	2		4				4	4			4
Quantum teleportation	592	512	158	82	8	16	8	10	8	6	10	18	2	14		2	
Quantum secret sharing	62	334	6	14	6									4			
entanglement swapping	350	92		30	4	10					4						
Entanglement concentration	34	204		30	14		4					6			8	8	
measurement device independent	1364	4212	664	676	266	262	220	194	116	76	62	60	18	38	58	12	42
Critical enablers, characterization, and benchmarking																	
Fidelity	3302	464	42	164	20	16	22	28	50	8	6	12		4	4		2
quantum memory	4882	7834	474	144	178	36	74	16	40	10	8	10	6	16		2	4
quantum repeater	632	306	54	134	30	12	4	16	10		4			8		10	2
quantum error correction	1998	348	60	74	48	8	8	44	80	6	4	12		10			

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Table A.16. Percentage of Patent Filings in Quantum Communications, by Technical Area

	USA	China	Japan	UK	South Korea	France	Germany	Canada	Australia	Italy	Israel	India	Malaysia	Poland	Singapore	Spain	Russia
Quantum-secured communication																	
Quantum cryptography	20%	12%	28%	22%	27%	28%	30%	5%	8%	29%	18%	21%	21%	25%	25%	31%	31%
Quantum key distribution	16%	28%	23%	27%	28%	12%	10%	13%	15%	21%	21%	9%	63%	15%	25%	44%	20%
Secure multiparty computation	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Entanglement-based protocols																	
entanglement swapping	1%	1%	0%	1%	0%	3%	0%	0%	1%	0%	0%	0%	2%	2%	0%	0%	4%
Quantum teleportation	3%	2%	5%	3%	1%	3%	1%	3%	2%	3%	6%	11%	1%	9%	0%	1%	0%
Quantum secret sharing	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%
entanglement swapping	2%	0%	0%	1%	0%	2%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%
Entanglement concentration	0%	1%	0%	1%	1%	0%	1%	0%	0%	0%	0%	4%	0%	0%	6%	6%	0%
measurement device independent	6%	17%	22%	25%	21%	41%	38%	52%	29%	36%	38%	35%	9%	23%	41%	9%	38%
Critical enablers, characterization, and benchmarking																	
Fidelity	16%	2%	1%	6%	2%	3%	4%	7%	12%	4%	4%	7%	0%	2%	3%	0%	2%
quantum memory	23%	32%	16%	5%	14%	6%	13%	4%	10%	5%	5%	6%	3%	10%	0%	1%	4%
quantum repeater	3%	1%	2%	5%	2%	2%	1%	4%	2%	0%	2%	0%	0%	5%	0%	7%	2%
quantum error correction	9%	1%	2%	3%	4%	1%	1%	12%	20%	3%	2%	7%	0%	6%	0%	0%	0%
Total Quantum Communications Patent Applications*	21114	24420	3010	2742	1282	636	572	374	402	210	164	170	196	162	142	140	110

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Table A.17. Patent Filings in Quantum Sensing, by Technical Area

	USA	China	Japan	UK	Germany	South Korea	Isreal	France	Canada	Austraila	Denmark	Italy	Finland	India	Sweden	Netherlands	Spain
Technical approaches and enablers																	
atom interferometer	2147	518	453	254	74	40	26	86	60	11	3	18	18	1	15	11	33
diamond	958	296	119	169	77	40	14	9	21	40		1		7		9	1
single photon	12221	6504	2407	1707	1543	519	415	432	271	174	92	209	146	81	153	82	85
cold atom	276	786	24	44	4	3	3	60	1	3							
Bose-Einstein condensate	469	24	29	21	11	4	1	19	21	7		6	7	2	14		1
quantum dot	706	5	12	20	20		8	6	16	25					1	9	1
Rydberg atom	149	132	8	15		1	1	6	10		3		2		1	8	
Imaging applications																	
Ghost imaging	289	385	65	24	10	6	4	1		1	4			1			
Quantum radar	77	78	25	1		6											
quantum imaging	147	178	13	24	5		3		5							1	
Quantum Illumination	22	10		2		1											
Non-imaging applications																	
magnetometry	3651	7244	4522	1463	702	1131	355	453	410	373	250	110	117	169	87	111	144
Gyroscope	1096	7027	1168	51	58	316	114	36	31	51	72	6	31	71	1	3	5
atomic clocks	976	571	115	38	21	8	86	19	16	13	3		2	1	2	1	
dark matter	718	565	58	24	7	10	2	32	18	10	5	12	5	4	1		4
gravimeter	888	174	46	29	12	4	2	15	4	7	1	2		4			2
quantum radiometry	3																
Trapped ion	743	19	3	22	1	6	3	2	25	4		1	1	5	1		
Quantum metrology																	
Quantum metrology	124	13	6	20	3	6		2	5			1		1	1		
spin squeezing	2761	928	383	192	87	95	29	11	26	35	11	12	5	24	9	23	

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Table A.18. Percentage of Patent Filings in Quantum Sensing, by Technical Area

	USA	China	Japan	UK	Germany	South Korea	Isreal	France	Canada	Austraila	Denmark	Italy	Finland	India	Sweden	Netherlands	Spain
Technical approaches and enablers																	
atom interferometer	8%	2%	5%	6%	3%	2%	2%	7%	6%	1%	1%	5%	5%	0%	5%	4%	12%
diamond	3%	1%	1%	4%	3%	2%	1%	1%	2%	5%	0%	0%	0%	2%	0%	3%	0%
single photon	43%	26%	25%	41%	59%	24%	39%	36%	29%	23%	21%	55%	44%	22%	53%	32%	31%
cold atom	1%	3%	0%	1%	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bose-Einstein condensate	2%	0%	0%	1%	0%	0%	0%	2%	2%	1%	0%	2%	2%	1%	5%	0%	0%
quantum dot	2%	0%	0%	0%	1%	0%	1%	1%	2%	3%	0%	0%	0%	0%	0%	3%	0%
Rydberg atom	1%	1%	0%	0%	0%	0%	0%	1%	1%	0%	1%	0%	1%	0%	0%	3%	0%
Imaging applications																	
Ghost imaging	1%	2%	1%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Quantum radar	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
quantum imaging	1%	1%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Quantum Illumination	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Non-imaging applications																	
magnetometry	13%	28%	48%	36%	27%	52%	33%	38%	44%	49%	56%	29%	35%	46%	30%	43%	52%
Gyroscope	4%	28%	12%	1%	2%	14%	11%	3%	3%	7%	16%	2%	9%	19%	0%	1%	2%
atomic clocks	3%	2%	1%	1%	1%	0%	8%	2%	2%	2%	1%	0%	1%	0%	1%	0%	0%
dark matter	3%	2%	1%	1%	0%	0%	0%	3%	2%	1%	1%	3%	1%	1%	0%	0%	1%
gravimeter	3%	1%	0%	1%	0%	0%	0%	1%	0%	1%	0%	1%	0%	1%	0%	0%	1%
quantum radiometry	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Trapped ion	3%	0%	0%	1%	0%	0%	0%	0%	3%	1%	0%	0%	0%	1%	0%	0%	0%
Quantum metrology																	
Quantum metrology	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
spin squeezing	10%	4%	4%	5%	3%	4%	3%	1%	3%	5%	2%	3%	1%	6%	3%	9%	0%
Total Quantum Sensing Patent Applications*	28421	25457	9456	4120	2635	2196	1066	1189	940	754	444	378	334	371	286	258	276

SOURCE: RAND analysis of patent data from the IFI CLAIMS database.

Technical Background on Silicon-Spin Qubits

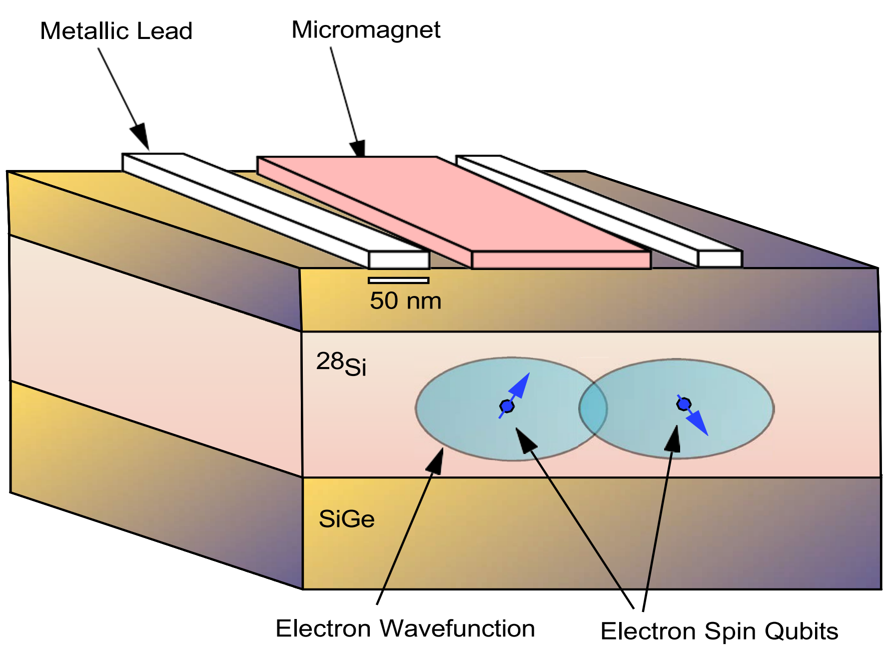
Silicon-spin qubits (SSQs) can consist of a single electron, the spin of a phosphorous nucleus, or the spin of another atom or nucleus fixed in some way in silicon or a silicon compound. The nuclear or electron spin must be isolated and interacted with in precise ways to set its spin state and to entangle it with other qubits without causing the qubit spin state to lose coherence so that it can be used in subsequent operations, including the final qubit readout.

Natural silicon has two isotopes: ^{28}Si and ^{29}Si. The extra neutron in the nucleus of ^{29}Si provides it with a net nuclear spin that can interact with spin qubits, causing the spin qubit (e.g., an electron) to lose coherence. For this reason, many groups make their quantum processors using isotopically purified ^{28}Si to increase the coherence times of their qubits.

SSQ quantum processors that use electrons as qubits also face the challenge of isolating a single electron in a semiconductor (where electrons often act more like a freely moving gas). Precisely engineered microscopic structures called *quantum dots* are built to isolate electrons using microscopic metallic lines, insulating isolation barriers, and micromagnets or microscopic microwave antennas.

Figure A.5 is an idealized illustration of a two-SSQ quantum dot device. Single electrons are isolated under the metallic leads shown at the top of the device. Microwave antennas (not shown) and micromagnets may also be implanted or etched on top of the device. Microwave pulses can be used to manipulate the orientation of the electron to execute a single qubit gate operation. In some electron states, the wave functions of the two electrons shown can spread out spatially so that they overlap and become entangled, allowing two-qubit gate operations. Both types of operations are needed to support quantum information processing.

Figure A.5. Idealized Illustration of Two Silicon-Spin Qubits in a Quantum Dot Device



NOTE: The quantum dot device shown isolated single electrons in a layer of purified ^{28}Si.

Quantum dots typically have microscopic dimensions. Figure 2.3 shows that the metallic leads or lines used to hold electrons in space are about 50 nm wide. Lines of this width are not unusual for SSQ quantum dots.

Quantum dots can be built using several types of materials. Silicon is often chosen because the fabrication tools of the microchip manufacturing industry can be used to build such devices using readily available commercial tools and well-understood methods. Because quantum dots are so small, advanced semiconductor manufacturing tools are usually needed to fabricate SSQ-based quantum processors.

Appendix B

Publication Analysis Methodology

The publication analysis in the main report defined three major application domains: quantum computing, quantum communications, and quantum sensing. These application domains were defined using a set of keywords selected by subject-matter experts (SMEs). We then used these keywords to query the Web of Science scientific publication database. The terms used to define each application domain are provided in Table B.1.[4]

Table B.1. Search Terms for Quantum Science Application Domains

Application Domain	Terms Included in Search
Quantum computing	"adiabatic quantum comput*," "amplitude amplification," "analog quantum simulation*," "blind quantum comput*," "boson sampling," "bqp," "bqp-complete," "charge qubit*," "circuit quantum electrodynamics," "cluster state*," "delegated quantum comput*," "deutsch-jozsa algorithm*," "distributed quantum comput*," "duality quantum comput*," "durr-hoyer algorithm*," "fault-tolerant quantum comput*," "flux qubit*," "geometric quantum comput*," "grover algorithm*," "grover's algorithm*," "grover's quantum search algorithm*," "hadamard gate*," "hhl algorithm*," "holonomic quantum comput*," "linear optical quantum comput*," "logical qubit*," "measurement-based quantum comput*," "nisq," "nmr quantum comput*," "noisy intermediate scale quantum," "one-way quantum comput*," "optical comput*," "qaoa," "quantum advantage," "quantum algorithm*," "quantum annealing," "quantum approximate optimization algorithm*," "quantum automata," "quantum cellular automata," "quantum circuit*," "quantum compilation," "quantum compiler*," "quantum complexity," "quantum complexity theory," "quantum comput*," "quantum computation and information," "quantum computation architectures and implementation*," "quantum computational complexity," "quantum computational logic*," "quantum computer simulation*," "quantum computing simulation*," "quantum cost*," "quantum counting algorithm*," "quantum decryption," "quantum error correction," "quantum evolutionary algorithm*," "quantum finite automata," "quantum fourier transform*," "quantum game*," "quantum gate*," "quantum genetic algorithm*," "quantum image proces*," "quantum information proces*," "quantum knot*," "quantum lattice gas automata," "quantum logic gate*," "quantum logic synthesis," "quantum logic*," "quantum machine learning," "quantum neural network*," "quantum neuron*," "quantum optimization," "quantum parallelism," "quantum phase estimation algorithm*," "quantum private comparison," "quantum programming," "quantum programming languages," "quantum query algorithm*," "quantum query complexity," "quantum recommendation," "quantum register*," "quantum search algorithm*," "quantum search*," "quantum simulation*," "quantum software," "quantum speedup," "quantum supremacy," "quantum

[4] The process used to generate the keywords is described in detail in Parker et al. (2022). The only difference from the set used in that publication is that we removed the term "D-Wave" because that term could either refer to the physical phenomenon of d-wave superconductivity (which is not directly related to quantum information science) or to the quantum computing company D-Wave Systems. (The search feature is not case-sensitive.)

Application Domain	Terms Included in Search
	turing machine*," "quantum verification," "quantum volume*," "quantum walk*," "shor's algorithm," "superconducting quantum comput*," "superconducting qubit*," "surface code," "topological quantum comput*," "topological qubit*," "universal quantum comput*," "variational quantum eigensolver," "variational quantum unsampling," "vqe"
Quantum communications	"bell inequalities," "bell inequality," "bell state*," "bell state measurement," "bell states," "controlled quantum communication*," "entanglement concentration*," "entanglement distillation*," "entanglement distribution," "entanglement swap*," "epr pair*," "free-space quantum communication*," "heralded single photon source*," "heralded single-photon source*," "long-distance quantum communication*," "qber," "quantum bit commitment," "quantum bit error rate*," "quantum channel*," "quantum communication*," "quantum communication channel*," "quantum communication complexity," "quantum communication network*," "quantum communications," "quantum dense coding*," "quantum dialogue," "quantum direct communication*," "quantum discord," "quantum internet," "quantum key distribution*," "quantum network*," "quantum networks," "quantum private quer*," "quantum repeater*," "quantum repeaters," "quantum router*," "quantum sealed-bid auction*," "quantum shannon theor*," "quantum state sharing," "quantum teleportation," "remote state preparation*," "superdense coding*," "the bell state measurement*," "quantum cryptogr*," "semi-quantum cryptogr*," "quantum secret sharing," "controlled quantum secure direct communication*," "quantum secure direct communication*," "deterministic secret quantum communication*," "deterministic secure quantum communication*," "quantum signature*," "quantum blind signature*," "quantum private comparison*," "quantum encryp*," "quantum authentication," "quantum identity authentication*," "secure quantum communication*," "arbitrated quantum signature*," "quantum secure communication*," "qsdc," "quantum communication security," "y-00 protocol*," "quantum steganogra*," "continuous variable quantum key distribution*," "continuous-variable quantum key distribution*," quantum key distribution*," "measurement-device-independent quantum key distribution*," "qkd," "qkd network*," "b92," "b92 protocol*," "bb84," "bb84 protocol*," "decoy state*," "quantum key agreement," "measurement device independent," "measurement-device-independent," "semi-quantum key distribution*," "decoy state protocol*," "decoy states*," "quantum one-time pad*," "quantum key distribution network*," "quantum key distribution protocol*," "photon number splitting attack*"
Quantum sensing	"quantum sensing," "quantum sensor*," "quantum metrology," "atom interferometry," "n00n state*," "atomic sensor*," "quantum gyroscope*," "quantum accelerometer*," "quantum ins," "quantum imu," "quantum magnetometer*," "quantum rf receiver*," "cold-atom interferometer*," "cold-atom gas interferometer*," "heisenberg limit*," "standard quantum limit*," "quantum inertial sens*," "quantum gravimeter*," "quantum electrometer*," "quantum radio*," "quantum receiver*," "rydberg atom sensor*," "vapor-cell sensor*," "defect-based sensor*," "scanning quantum dot microsco*," "qubit detector*," "quantum detector*," "quantum detector tomography," "quantum tomography," "quantum state tomography," "microwave bolometer*," "microwave bolometer*" "quantum illumination," "ghost imaging," "quantum dot imaging," "quantum imaging," "quantum radar*"

SOURCE: RAND analysis described in Edward Parker, Daniel Gonzales, Ajay K. Kochhar, Sydney Litterer, Kathryn O'Connor, Jon Schmid, Keller Scholl, Richard Silberglitt, Joan Chang, Christopher A. Eusebi, and Scott W. Harold, *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*, RAND Corporation, RR-A869-1, 2022.

This report uses four publication-based metrics: national publication counts, high-impact publications, eigenvector centrality, and a topical breakdown of a country's publication output. The remainder of this appendix describes how these metrics were defined and populated in the main report.

National publication counts are the total number of publications matching the search strategy that were published by authors hosted by the given country. The "nationality" of a publication is determined by the "country" field within the Web of Science database, which is taken from the affiliation address field of the authors of the publication. When a publication was written by authors from more than one country, the publication is allocated to each country listed. This means that certain publications are counted more than once.

Scientific publications do not have equal impact. In fact, in some cases, there are substantial country-specific differences in average publication quality.[5] To account for heterogeneity in publication quality, we calculated the number of publications that fell into the top 10 percent of the citation distribution for each country.[6] The "High-Impact Research Activity" subsection of Chapter 2 summarizes these results.

To measure the importance of an organization within the international scientific network for a given topic, we calculated eigenvector centrality on the publications' coauthorship network. Eigenvector centrality is a common graph theory metric that measures how important a node is within a network. As opposed to other centrality measures, such as degree centrality, eigenvector centrality incorporates information about how connected an incoming node is. That is, the impact of a well-connected node on the linked node's eigenvector centrality score is greater than the impact of a non–well-connected node. In the network visualizations presented in Chapters 2 and 3, node size is determined by publication counts, and edge weight is determined by the number of collaborations between the linked nodes. Network visualizations and the calculation of centrality were done using the Gephi network analysis software package.

The topical focus subsection of Chapter 2 used a keyword-based approach to define the topics. For each database of publications within a given application domain (quantum computing communications, or sensing), we collected the set of all author-provided keywords for each paper. This process produced a list of over 50,000 keywords across all three application domains. We then filtered these lists of keywords to those that the authors provided for 20 or more publications for quantum computing and communications, or eight or more publications for quantum sensing.[7] We then had an SME on the team search through the list of author-provided keywords and select those that he judged provided a useful level of topical granularity (e.g., he judged that in quantum computing, the term "qubit" did not provide enough granularity to be useful, while the term "Leggett-

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[5] Jon Schmid and Fei-Ling Wang, "Beyond National Innovation Systems: Incentives and China's Innovation Performance," *Journal of Contemporary China*, Vol. 26, No. 104, 2017.

[6] Jon Schmid, *An Open-Source Method for Assessing National Scientific and Technological Standing: With Applications to Artificial Intelligence and Machine Learning*, RAND Corporation, RR-A1482-3, 2021.

[7] There were many fewer publications in the quantum sensing database than in the quantum computing or communication databases and, therefore, many fewer keywords that corresponded with a significant number of publications. So we set the cutoff threshold lower for quantum sensing to keep a comparable number of filtered keywords in each of the three application domains.

Garg inequality" provided too much, and the term "superconducting qubit" was appropriately granular).

Next, the SME grouped together keywords that he judged to be related closely enough to aggregate together into a single topical category. If any term from within a topic was found within the publication title and publication abstract, that patent was labeled as belonging to that topic. Table B.2 presents the terms used to define the topics within the larger application domain of quantum computing. Tables B.3 and B.4 present the same information for the quantum communications and quantum sensing domains.

Table B.2. Terms Used to Define Quantum Computing Topics

Topic	Author-Provided Keywords Used to Define Topic
Algorithms and end-user applications	
Quantum simulation	Quantum simulation, quantum chemistry, quantum simulations
Quantum machine learning	Quantum machine learning, Quantum neural network, Quantum neural networks
Optimization	Optimization, quantum optimization, Combinatorial optimization
computational complexity	Computational complexity, quantum query complexity
Grover's algorithm	Grover's algorithm, quantum search, Grover algorithm
Shor's algorithm	Shor's algorithm, Shor algorithm
Variational quantum eigensolver	Variational quantum eigensolver
QAOA	QAOA, Quantum Approximate Optimization Algorithm
Basic computational paradigms	
Quantum annealing	Quantum annealing
Cluster state	Cluster state
adiabatic quantum computing	adiabatic quantum computing, adiabatic quantum computation
boson sampling	boson sampling
noisy intermediate-scale quantum	NISQ, noisy intermediate-scale quantum
fault tolerant	fault tolerant
Hardware approaches	
Optical computing	Optical computing, linear optics, photonic integrated circuit
single-photon	Single photons, single photon, single-photon source, single photon source
Quantum dot	Quantum dot, Quantum dots
spin qubits	Spin qubits
Superconducting qubit	Superconducting qubits, Superconducting qubit, Flux qubit
Trapped ion	Trapped ions, Ion trap
Rydberg atom	Rydberg atoms, cold atoms, ultracold atoms
nitrogen-vacancy center	Nitrogen-vacancy center, nitrogen vacancy center
Majorana fermions	Majorana fermions, topological quantum computation

Topic	Author-Provided Keywords Used to Define Topic
Critical enablers, characterization, and benchmarking	
Quantum error correction	Quantum error correction, surface code
Quantum control	Quantum control
Fidelity	Fidelity, Quantum tomography, Quantum state tomography
Quantum memory	Quantum memory

Table B.3. Terms Used to Define Quantum Communications Topics

Topic	Terms Used to Define Topic
Quantum-secured communication	
Quantum cryptography	Quantum cryptography, Eavesdropping detection
Quantum key distribution	Quantum key distribution, QKD, quantum secure direct communication, quantum key distribution (QKD), continuous-variable quantum key distribution, quantum key agreement, Decoy state, BB84, BB84 protocol, CV-QKD, Quantum bit commitment
Entanglement-based protocols	
Entanglement	Entanglement, Quantum entanglement, entanglement distribution, entangled states
Quantum teleportation	Quantum teleportation
Quantum secret sharing	Quantum secret sharing
Entanglement swapping	Entanglement swapping
Entanglement concentration	Entanglement concentration
Measurement-device-independent	Measurement-device-independent, Measurement-device-independent quantum key distribution, measurement device independent
Secure multiparty computation	Secure multiparty computation
Critical enablers, characterization, and benchmarking	
Fidelity	Fidelity
Quantum memory	Quantum memory
Quantum repeater	Quantum repeater, quantum repeaters
Quantum error correction	Quantum error correction

Table B.4. Terms Used to Define Quantum Sensing Topics

Topic	Terms Used to Define Topic
Technical approaches and enablers	
Atom interferometer	Atom interferometry, Mach-Zehnder interferometer, atom interferometer, cold atom interferometry
Nitrogen-vacancy center	Diamond, nitrogen-vacancy center, NV center, nitrogen vacancy, Nitrogen-vacancy centers, NV centers, nitrogen vacancy center

Topic	Terms Used to Define Topic
Single photon	Single photon, single photons, single-photon detector, photon-number-resolving detectors
Cold atom	Cold atom
Bose-Einstein condensate	Bose-Einstein condensates, Bose-Einstein condensate, Bose Einstein condensate
Quantum dot	Quantum dots, quantum dot
Rydberg atom	Ryberg atom
Imaging applications	
Ghost imaging	Ghost imaging, Computational ghost imaging, Compressive ghost imaging, Temporal ghost imaging
Quantum radar	Quantum radar, noise radar, quantum radar cross section
Quantum imaging	Quantum imaging, imaging system
Quantum illumination	Quantum illumination
Nonimaging applications	
Magnetometry	Magnetometry, optically detected magnetic resonance, magnetometer, quantum magnetometer, magnetometers, magnetic resonance, magnetic resonance imaging, magnetic sensors
Gyroscope	Gyroscope, inertial sensors
Atomic clocks	Atomic clocks, atomic clock
Dark matter	Dark matter
Gravimeter	Gravimeter, gravimetry
Quantum radiometry	Quantum radiometry
Quantum metrology	
Quantum metrology	Quantum metrology
Spin squeezing	Spin squeezing, squeezed light, squeezing

Finally, we used the set of SME-provided keywords to search within the title and abstracts of the publication from within the focal application domain. For example, to define the result for "quantum radar," the terms "quantum radar," "noise radar," and "quantum radar cross section" were searched within the title and abstracts of the quantum sensing publication dataset. If any of the searched terms were present within the titles and abstracts of the focal dataset, the specific publications were classified as belonging to the focal topic. We searched only within the database of papers that we had previously independently identified as being focus on quantum information science. For example, most academic publications containing the word "gyroscope" are not related to quantum sensing, but we searched for that keyword only within the previously compiled database of publications on quantum sensing.

Appendix C

Australia's Quantum Industrial Base

One RAND research team member for this project was physically located in Australia, so our team decided to do a deeper dive into the Australian quantum industrial base (QIB) and speak with various representatives from industry and government. This appendix summarizes that deeper dive. We begin by providing a summary of the current status of the QIB, then outline the 2023 National Quantum Strategy (NQS, the Australian government's vehicle for the development and commercialization of quantum information science) and conclude with stakeholder perspectives on the state of Australia's QIB.[8] This appendix can be read independently of the main report.

Current Status

Australia has played a leading role in quantum information science research for some time, advancing knowledge and developing intellectual property (IP) in all three application domains: quantum computing, communications, and sensing. To date, this research has primarily been funded through Australian Research Centre (ARC)'s centers of excellence (CoEs), which have provided a continuous stream of funding since 2003, largely dividing the focus between quantum computing and communications technology and engineered quantum systems, although the second most recent (2022) ARC CoE grant announcements included AUS $35 million (U.S. $23 million) for quantum biotechnology (see Table C.1). These funding streams are explicit in focusing on basic scientific research that is free of commercialization considerations and free to evolve the research where the science takes it.[9]

[8] Department of Industry, Science and Resources, *National Quantum Strategy: Building a Thriving Future with Australia's Quantum Advantage*, Australian Government, 2023a.

[9] Foley, 2022, p. 2.

Table C.1. ARC CoE Funding

ARC CoE	Year	Funding (AUS $M)
Quantum computer technology	2003–2011	24.10
Quantum-atom optics	2003–2011	16.95
Quantum computation and communication technology	2011–2017	24.50
	2017–2025	33.70
Engineered quantum systems	2011–2017	24.50
	2017–2024	31.90
Future low-energy electronics technologies	2017–2024	33.40
Quantum biotechnology	2022–2029	35.00

SOURCE: Cathy Foley, "Growing Australia's STEM Industries: Lessons from Quantum," Office of Australia's Office of the Chief Scientist, 2022, p. 3; Australian Research Council, "ARC Centre of Excellence in Quantum Biotechnology," webpage, Australian Government, undated.

This funding has been supplemented by sectoral funding, particularly through the Australian Department of Defence and international collaborations.[10] While primarily focused on fundamental research, these funding initiatives have resulted in a nascent Australian quantum industrial ecosystem, with a number of universities establishing critical infrastructure and spin-off companies to exploit the IP they have developed.[11] In some cases, this is leading to significant investment from venture capital and similar companies (detailed in the main report). The recent establishment of an industry body, the Australian Quantum Alliance,[12] demonstrates an industry effort to shape the policy environment to meet industry needs:

- Australian companies
  - Diraq
  - Nomad Atomics
  - Q-CTRL
  - Quantum Brilliance
  - QuintessenceLabs
  - Silicon Quantum Computing

[10] For example, the Next Generation Technology Fund, under the Quantum technologies priority area. Defence Science and Technology Group, "Next Generation Technologies Fund," webpage, Australian Government, undated, and Australian Government: Business, "Australia-US Multidisciplinary University Research Initiative (AUSMURI)," webpage, undated.

[11] For instance, Noetic, "Quantum Computing Insights Paper," *Emerging Disruptive Technology Assessment Symposium (EDTAS)*, Australian Department of Defence, 2022, Annex B.

[12] Technology Council of Australia, "Australian Quantum Alliance," webpage, undated-a; Technology Council of Australia, "Launch of the Australian Quantum Alliance," webpage, undated-b.

- foreign countries
  - Google
  - Microsoft
  - Rigetti.

As of this writing, the extent to which the AUS $1 billion (U.S. $670 million) earmarked to support Australia's quantum ecosystem (as announced in the 2023 NQS) will be targeted toward fundamental research is unclear.[13]

Concurrent with this, there is a recognition in the policy space that research in quantum information science is transitioning to real-world applications. Policymakers are developing policy instruments that both commercialize Australia's investment in quantum science and ensure that appropriate controls exist to protect the IP generated from inappropriate exploitation by others. The commercialization of quantum sciences is facing this friction between technology promotion and protection. On the one hand, the Australian government's Commonwealth Scientific and Industrial Research Organisation (CSIRO) has developed plans "for unlocking the potential of emerging quantum technologies and position[ing] Australia to capture a six billion-dollar opportunity by 2045."[14] This plan articulated four policy needs:

- focus and coordinate quantum industry development
- build quantum workforce and infrastructure
- support productive collaboration with local and international partners
- enhance the readiness of governments, society, and end users for next-generation quantum technologies.

An updated economic analysis released in 2022 forecast that the Australian quantum workforce would grow to 8,700 by 2030 and to 19,400 in 2045.[15] The CSIRO analysis suggested that quantum computing could dominate the workforce, rising to 65 percent of job "opportunities" by 2045. CSIRO predicted that, over that period, quantum communications will remain steady at 22 percent, while quantum sensing and measurement would represent 13 percent of the workforce. (As we discuss later, some in industry consider this prediction to be optimistic.) In terms of financial outputs, quantum sensing and measurement represents the higher per capita return, based on these workforce projections, at AUS $440,000 per worker, compared with AUS $283,000 and $285,000 for quantum computing and quantum communications, respectively.

However, the national security community has raised concerns over transfer of sensitive technologies to some foreign powers, often through the guise of academic collaboration. The government established a list of 63 critical technologies of national interest (CTNI) that limit "what

[13] Department of Industry, Science and Resources, 2023a.

[14] In their 2020 analysis, CSIRO put the economic benefit for Australia by 2040 at AUS $4 billion; see CSIRO, *Growing Australia's Quantum Technology Industry: Positioning Australia for a Four Billion-Dollar Opportunity*, May 2020. The 2022 update increased this to AUS $6 billion by 2045; see CSIRO, *Growing Australia's Quantum Technology Industry: Updated Economic Modelling, Revised Economic Estimates to the 2020 Report*, October 2022.

[15] CSIRO, 2022.

the government, industry and universities can and cannot share with foreign counterparts."[16] The commonwealth has identified four fields of quantum information science within the CTNI list: post-quantum cryptography, quantum communications, quantum computing, and quantum sensors.[17] The intent of the CTNI list is to balance the competing demands of national security, economic prosperity, and social cohesion—that is, to "drive increased productivity, growth, and improved living standards [while minimizing] the potential to harm our economic and national security interests and undermine our democratic values and principles."[18] In parallel to this, the Department of Defence has established a sensitive technologies policy that seeks to manage export of technologies through the Defence and Strategic Good List.[19]

National Quantum Strategy

The culmination of all of these factors was the Australian government's development of the NQS. Initiated in November 2021, the (previous) government announced a commitment of "$111 million [AUD] to secure Australia's quantum future, supporting the commercialisation, adoption and use of this new technology to create jobs, support Australian business and keep Australians safe."[20] This is echoed in some recent commentary by the Australian Strategic Policy Institute, which noted that "quantum technologies will arrive within five to 10 years and . . . will be highly disruptive to the commercial sector and to national security," so the AUKUS (Australia, UK, and the United States) partners need "to develop standards to address the potential regulatory, ethical, intelligence, commercial and legal implications of novel quantum technologies."[21] The NQS, released in May 2023, included a significant increase in government support, including an immediate action to "grow a pipeline of quantum companies and technologies" using some of the AUS $1 billion set aside for investment in critical technologies.[22]

To achieve Australia's ambition that by 2030, "Australia is recognised as a leader of the global quantum industry, and quantum technologies are integral to a prosperous, fair and inclusive Australia,."[23] The NQS sets out to achieve five strategic objectives and associated implementation actions:

- **Creating thriving research and development, investment in, and use of quantum technologies.** Follow-on actions include incentivizing growth in use cases, creating initiatives

[16] "Australia to Wall Off Sensitive Tech from China," webpage, The Vibes, November 17, 2021.

[17] Department of Industry, Science and Resources, "List of Critical Technologies in the National Interest," Australian Government, May 19, 2023b.

[18] Department of Industry, Science and Resources, "2022 List of Critical Technologies in the National Interest," consultation paper, Australian Government, 2022, p. 2.

[19] Defence Export Controls, "The Defence and Strategic Goods List," webpage, Australian Government, 2021.

[20] Melissa Price, "$111 Million Investment to Back Australia's Quantum Technology Future," press release, Minister for Science and Technology, Australian Government, November 17, 2021.

[21] Bronte Munro and Tristan Paci, "AUKUS Must Focus on Quantum Policy, Not Just the Technology," *The Strategist*, March 1, 2023.

[22] Department of Industry, Science and Resources, 2023a.

[23] Department of Industry, Science and Resources, 2023a, p. 6.

to drive ecosystem growth and commercialization, and strengthening international relationships.[24]

- **Securing access to essential quantum infrastructure and materials.** A national audit of quantum-related infrastructure and active monitoring of supply chain challenges and opportunities will occur. This also includes an "ambitious" plan to build the world's first error-corrected quantum computer in Australia."[25]
- **A skilled and growing quantum workforce.** This includes promoting Australia as "the world's top destination" for companies within the QIB and their workforces.[26]
- **Standards and frameworks that support national interests.** This focuses on establishing a fit-for-purpose regulatory environment that balances the collaborative development and export of quantum technologies with the need to protect Australia's national interests.[27]
- **A trusted, ethical, and inclusive quantum ecosystem.** This entails ensuring that "the growth of Australia's quantum ecosystem supports economic prosperity while safeguarding national wellbeing."[28]

The government has taken a comprehensive perspective to building the necessary ecosystem, including workforce, infrastructure, and international partnerships, demonstrating an intent for the Australian QIB to actively engage with the United States. For instance, the government seeks to "strengthen collaboration and opportunity for industry with our established partners through existing arrangements . . . including AUKUS, the Quad, and other regional and special bilateral agreements." [29] It is also intends to actively engage with and participate in international quantum standards-setting bodies, and be seek opportunities to be a regional leader.

The NQS explicitly calls out the importance of and implications for the AUKUS Quantum Arrangement on building the QIB, noting that "AQuA will work to accelerate investments to deliver generation-after-next quantum military capabilities," with an initial focus on PNT. There is also an aspiration to "integrate emerging quantum technologies in trials and experimentation over the next 3 years."[30]

Stakeholder Perspectives

We engaged industry and government stakeholders to ascertain their perspectives on the state of Australia's QIB, the trajectory it was on, their place in the industry, and the opportunities and challenges they foresaw. This occurred during the development of the NQS. There was some reluctance to fully engage because these stakeholders did not wish to comment prior to the release of

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[24] Department of Industry, Science and Resources, 2023a, p. 22.

[25] Department of Industry, Science and Resources, 2023a, p. 28.

[26] Department of Industry, Science and Resources, 2023a, p. 32.

[27] Department of Industry, Science and Resources, 2023a, p. 36.

[28] Department of Industry, Science and Resources, 2023a, p. 41.

[29] Department of Industry, Science and Resources, 2023a, p. 36.

[30] Department of Industry, Science and Resources, 2023a, p. 20.

the strategy and because our approach came at the end of a period of repeated stakeholder engagement (e.g., both government and industry stakeholders mentioned "consultation fatigue").

We approached ten Australian companies in all: Archer Materials, Diraq, MOG Labs, Nomad Atomics, Q-CTRL, Quantum Brilliance, QuantX Labs, QuintessenceLabs, Silex Systems, and Silicon Quantum Computing. Four of these companies agreed to speak with us; to preserve the confidentiality of their assessments, we are not identifying which four. We also held discussions with two sets of government representatives, one from the Defence Science and Technology Group within the Department of Defence and the other from the Department of Industry, Science, and Resources. We were not able to arrange an interview with the office of Australia's chief scientist.

We held semistructured interviews with industry stakeholders in December 2022. The discussions focused on six questions:

- How would you characterize the current state of Australia's QIB? Where does Australia's QIB offer a unique value proposition?
- What do you see as the key drivers that should shape quantum industry policy in Australia?
- What are the key successes and technical achievements of Australia's QIB in general and of your companies in particular?
- What does the Australian quantum industry development path look like? What factors may accelerate or inhibit that?
- What are your key relationships with academia, government, other companies, and international institutions? How do you see them evolving?
- What does the supply chain look like, both downstream and upstream? Are you experiencing or foreseeing any challenges?

We informed interviewees that they would not be quoted or identified in the report and that we would not disclose any potentially propriety information. While this encouraged open discussion, the need to de-identify participants limits our ability to disclose the examples and case studies they provided to explain particular points. However, a number of themes emerged (note that we are not necessary endorsing these conclusions):

The Australian Department of Defence is active in underwriting commercialization of quantum technologies. The majority of quantum companies are spin-offs from the various ARC CoE's. However, the Department of Defence, in particular, has made investments supporting a number of these companies, covering all three quantum technology domains. However, the lack of responsiveness of the department's internal processes means that companies are required to carry financial risks associated with necessary up-front investments (infrastructure, workforce). This can be problematic, given the extant funding base. Currently, the Australian financial sector is not seen as an option because it is less forthcoming in funding start-ups in general.

Australia should pick some winners because it cannot sustain a broad industrial base. While Australia has demonstrated that it can sustain world-class research across the breadth of quantum technologies, it will need to make strategic decisions about which areas to focus on if it wishes to be commercially successful. Otherwise, it risks creating an "armada of canoes." For quantum sensors and quantum cryptography, this would entail specific commercial products. However, given the complexity of quantum computing, this should be narrowed down to particular components or attributes. Australia should not seek to operate at the level of constructing or consolidating whole quantum computers: There will probably be significant consolidation in this field, and Australia's small base will not be competitive. Some interviewees suggested that Australia should focus on applications or software and commercial research and development or IP production.

Australia's small community and strong international relationships allow novel approaches to developing products. Interviewees strongly suggested that Australia's innovation system is functioning poorly, particularly in terms of supporting the technology translation from benchtop to production line. Most companies within Australia's QIB have strong, often formal, global relationships. Some companies noted that their operational model is one of Australia undertaking the commercial research and development, with international partners transitioning the resulting IP into production. Others take a bottom-up approach to developing sectoral use cases with strategic partners and products that are affordable, offer improvements, and allow the knowledge base to grow, thereby minimizing risks. They also suggested that such a model can overcome some of the challenges of domestic and international (particularly U.S.) restrictions on the transfer of sensitive technologies. There is a lack of integration across the sector, although the establishment of the Australia Quantum Alliance, along with some of the products from the NQS (Prospectus, commercialization hub), should help overcome this.

Australia's policy environment is inhibiting commercialization. The commonwealth has a range of policies that are incoherent, seeking to build industrial capability and markets but, at the same seeking to restrict access. There appears to be no simple, whole-of-government approach that is less risk averse. There also a lack of understanding of the commercial drivers needed to grow a new industrial sector, with companies facing regulations, accreditations, and other administrative red tape designed for more-established industries. The arbitrary imposition of sensitive technology policies, which restrict access to capital and need to be offset with alternative sources of funding, may cause some companies and experienced individuals to move offshore. This contradicts the government's avowed policy to grow the QIB through the inflow of companies, people, and capital.

The Australian labor market is tight and prefers other sectors that are seen as more stable or lucrative. As with many advanced economies, there is high demand for people with science, technology, engineering, and math skills. While there is general agreement that the Australian QIB will grow, although not at the rate suggested in the CSIRO analysis, many companies are already struggling to fill places. Given Australia's lack of depth in many skill sets, there is little prospect of lateral movement between companies and adjacent industries, and it will take time to build the workforce organically.

Company leadership needs to transition from an academic to a commercial mindset. Development of Australia's QIB has been led by the academic community, but if the industry is to succeed, leadership needs to transition to those with stronger business acumen, given that these two cohorts have quite different drivers. For example, the research CEO might transition to becoming the CTO. The government should also recognize this state of play and adjust its expectations so that those in the academic community can fully realize the commercialization of quantum technologies.

Companies now understand secure supply chain issues and challenges. As a result of the COVID-19 pandemic, interviewees were very sensitized to their supply chain vulnerabilities, although they sometimes struggle to get prioritized access to key technologies. They recognized that, while

Australia has the capability to fill many of the gaps, doing so would not be economically viable, except in very specific cases or critical needs. Many companies have established business models that recognize the need to avoid supply chain dependency on China and other countries of concern.

The NQS needs to manage the hype associated with quantum technologies, especially quantum computing. One stakeholder stated that the biggest risk to Australia's QIB is the hype associated with these technologies, with some fundamental misunderstandings of viable use cases, too many announcements, and unrealistic timelines. Interviewees saw quantum computing as being of particular concern. Because its strength lies in complex calculations with a limited number of inputs and outputs, it is not expected to compete with classical supercomputers. Not managing this quantum hype risks damaging confidence in the sector from the community, government, investors, and potential end users. Stakeholders should make efforts to make the public (and government) conversation on quantum technologies better informed.

Abbreviations

ARC	Australian Research Council
AUKUS	Australia, the United Kingdom, and the United States
AUS	Australian currency
CoE	center of excellence
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CTNI	Critical Technologies of National Interest (Australia)
IP	intellectual property
NQS	(Australian Government) National Quantum Strategy
QIB	quantum industrial base
SME	subject-matter expert
SSQ	silicon-spin qubit
UK	United Kingdom
USD	U.S. dollars

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