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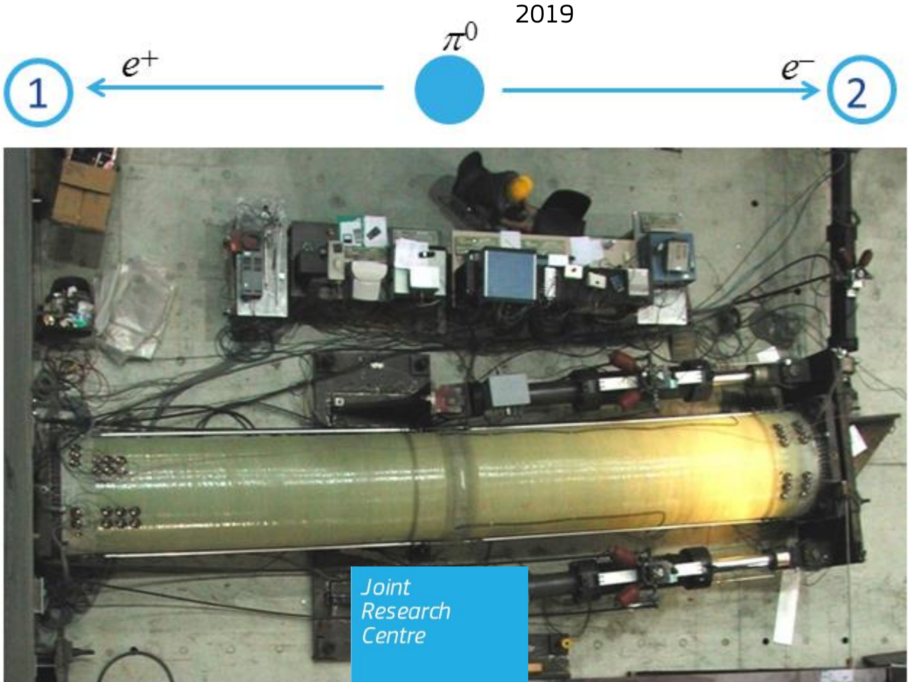
Collaboration and Semantic Networks of EU-funded Research in Quantum Technologies: 2007-2019

Horizon scanning for Perspectives on Quantum Technology for Structural and Mechanical Engineering

Gutiérrez E., Bono F., Strozzi, F

2019



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Abstract

A quantitative analysis is conducted of the distribution of budgets, participants and host countries from a compilation of EU-funded CORDIS projects with starting dates from Q2 2007 till Q3 2019. The projects are selected on the basis of containing the word *'quantum'* in their objectives description texts. An accompanying semantic analysis of the concatenated texts is conducted by mapping the projects budget timeline to the word associations of the word *quantum* to its related technical fields.

1 INTRODUCTION

Currently there is a world-wide push to exploit further the findings of quantum mechanics to technological areas of applied sciences and engineering. Of particular interest to engineers—and specifically to the mechanically-oriented branches in structural, civil and aerospace—is the application in the field of inertial metrology (i.e. accelerometers, gyroscopes and gravimeters) but also on the potential of quantum computing and simulation to provide new means to solve complex problems in structural mechanics and materials science.

Quantum mechanics is at the heart of understanding the behaviour of important technological applications: from semiconductors and lasers to computational chemistry and magnetic resonance imaging. Yet although it is beyond doubt that the knowledge of quantum mechanics explains many phenomena used in practical objects and processes, the purposeful manipulation of singular quantum effects to generate controllable or tuneable processes for sensing and computing is still some way off from the goals claimed a decade or more ago. Indeed, some claim that whereas many scientific methods were improved or better understood by the knowledge of quantum mechanics in a macroscopic sense, many of these enhancements have also come about through developments in applied science and engineering rather than solely due to major new discoveries in quantum mechanics; for example, the exponential increase in computational power from semiconductor devices has been made possible through the improvements in photolithography and precision production engineering.

Most of the above refers to the, so-called, first quantum revolution. The second one, it is claimed, will change information technology and computation; moving away from relying on macroscopic effects to the information space arising from quantum entanglement and superposition. The manipulation of quantum objects to compute and execute algorithms at the basic quantum scale is at the heart of the second quantum revolution. The recently launched Quantum Technology Flagship[1] (QTF) aims to concentrate funding in this direction and intends to maintain Europe at the forefront of quantum technologies. However, although the QTF provides an added impetus, over the past decades the European Commission's various R&D programmes have funded many projects where quantum mechanics plays a key role. What can be garnered from past projects? Which trends attracted most funding in the broader field of quantum technology applications?

This report provides technically-minded researchers, but non-specialists in QT, a panoramic of the subject matter treated in these projects. In a second instalment we will try to link the objects of this study (i.e. the research areas, researchers and funding) to discernible outputs such as publications, patents or concrete examples of technological advancement, which could play a role in structural mechanics and engineering.

The various EU research funding schemes constitute a highly complex transnational ensemble of projects which not only intend to fund the best research but also, in sympathy with the subsidiarity principles of the EU[2], to generate cohesive actions bringing together countries and laboratories into the fold of a European-wide research. This is particularly relevant for certain key technological areas which benefit from being carried out at a European level rather than by a single Member State (MS). Irrespective of this, the calls are expected to set the highest requirements for project proposal and consortia.

[1] https://qt.eu/
[2] http://www.europarl.europa.eu/factsheets/en/sheet/7/the-principle-of-subsidiarity

The research policy context posits two broad distinct themes: on the one side the aspects of country embeddedness in trans-national research networks (Graf and Kalthaus, 2018), and on the other the impact on innovation of the clustering—both in size, quality, and geographic diversity—of research networks (Nepelski et al., 2019),(Lucena-Piquero and Vicente, 2019),(Enger, 2018). We therefore quantify two possibly opposing goals of EU R&D funding: in the first place, in view of the drive towards a homogenisation of means between the EU member states, whether the high funding achieved by some countries and partner institutions is a suitable distribution of funds, and, in contrast, whether curtailing the success of 'over-performers' would result in a reduction of funding to those institutions most capable of competing and obtaining world-class results.

Before proceeding we should note that this report is not an in-depth technical review of the various key quantum technologies; such aspects have been extensively analysed and presented by many authors including those by the JRC (Lewis, 2017; Lewis and Travagnin, 2018)(Lewis, A, Ferigato, C, Travagnin, M and Florescu, 2018). Neither is this report intended to suggest future road maps (Acín et al., 2018) nor pass judgement on past ones; instead, its scope is to provide a broad statistical overview of a large number of EU-funded projects scattered over many programmes and calls organised by multiple funding Directorates General (DGs) over the past decade or so. The overall results and analyses presented herein are therefore not a reflection of any targeted funding vehicle. The information assembled for this report is collated from the publicly-available CORDIS website which is subject to a legal disclaimer[3].

2 MATERIALS AND METHODS

COLLECTION OF PROJECTS

Projects were selected from the CORDIS database based solely on whether they contained the word *'quantum'* in the 2000-character long Objectives' text associated to each project's CORDIS entry. We claim that selecting projects based on such a simple criteria captures a broad collection of quantum-related subjects that otherwise might have escaped a more subjectively limited set of keywords. However, using such a fine dragnet will necessarily include some projects that may not concern QT at all; for example, the term *'quantum leap'*, is usually used in an colloquial sense. To ascertain the QT-relevance of such projects, we conduct a semantic and time series analysis based on the text corpus of the concatenated list of the projects' Objectives texts. The text corpus is used to construct a comprehensive list of quantum-adjectivised terms that were examined for their technical relevance; then, by inspecting the time series generated by the appearance rate of the various terms, it is possible to ascertain if some projects need to be removed from the data.

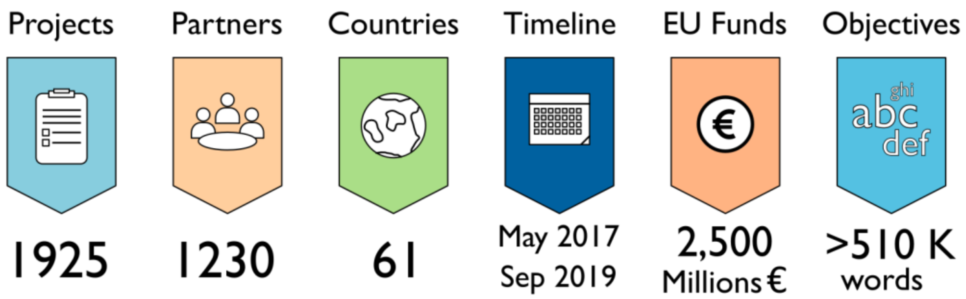
We refer to core, mantle and crust projects depending on their relevance to QT. We assume that there will be a core group whose research content is directly related to QT. Mantle projects may relate to QT but in a less direct way, perhaps developing key enabling technologies for QT; formulating QT research networks; policy studies; computer science; how QT will impact another technical field; or perhaps suggesting alternatives or casting doubt on the claims of QT technologies. The division between the core and mantle sections is highly subjective, but it is worthwhile not to be too restrictive at this stage. Finally, the crust projects are those we wish to identify because they have no technical relation to QT.

[3] https://cordis.europa.eu/about/legal/en

Having extracted the gross project data set the next step is to decide on which aspects we wish to concentrate the analysis. We have decided in the first instance to collate the following parameters:

- The project names (Projects)
- The participant organizations (Partners)
- Funding by EU in Euros:
    - Per Project
    - Per Partner for each project
- The official contractual start dates
- The Country code of each Partner

In a subsequent report we shall consider how our findings are complemented by other data fields such as the funding programme; the funding call topic; the subject index classification codes; the coordinating partner and the nominal end date, amongst others. The main headlines for the gross data set presented in this report are schematised below:



The weighted Projects-Partners-Countries network

A Projects-Partners-Countries network adjacency matrix is generated from the relation tables compiled from the CORDIS data set by linking projects with partners, and partners with their host countries. Each node corresponds to a Project, Partner or Country. The links between nodes are weighted either (a) according to the budgets received from the EU by each partner for each project or (b) a value of 1 associating a Partner to a Country. The general concept is shown in Figure 1. Another set of links connect each project to one or more search keywords (for this study there is only one search keyword: '*quantum*'). The keyword(s), in turn, form part of the much larger *Semantic Network* we describe in the next section. In Figure 2 we show the symmetric dot-density adjacency matrix of the projects, their connections to participants and their respective host country. The blank coloured areas indicate that there are no explicit links between projects (orange-top left corner); nor between partners (green-bottom right corner), nor between countries (the small blank block at the very bottom right corner). In subsequent analyses we will use the weighted matrix—by way of its Laplacian—to map the three heterogeneous sets (projects, partners and countries into modal forms that combine all three classes. By examining the distribution of the major modes it is possible to highlight the most important combinations of funding across the whole data set; thus revealing hidden patterns that may be indicative of research trends and funding flows. Implicit connections revealed by modal analysis may then be used to extract technology embeddedness, the presence of cliques or antagonistic competition. For the time being we use it as an alternative to standard relational databases.

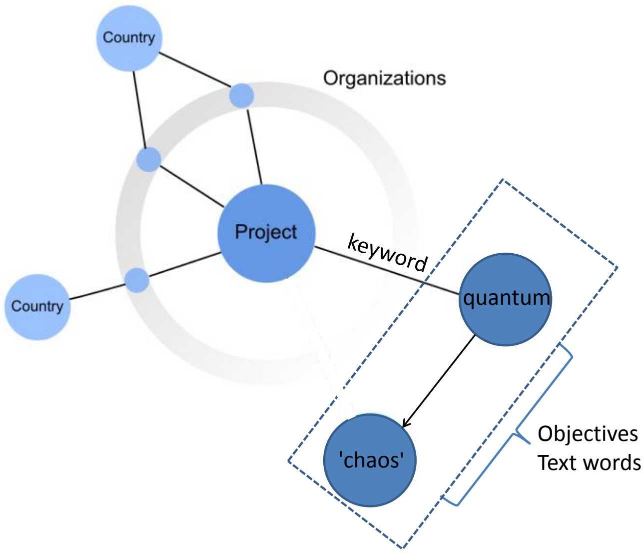


Figure 1 - Project-Partners-Countries network and relation to keywords.

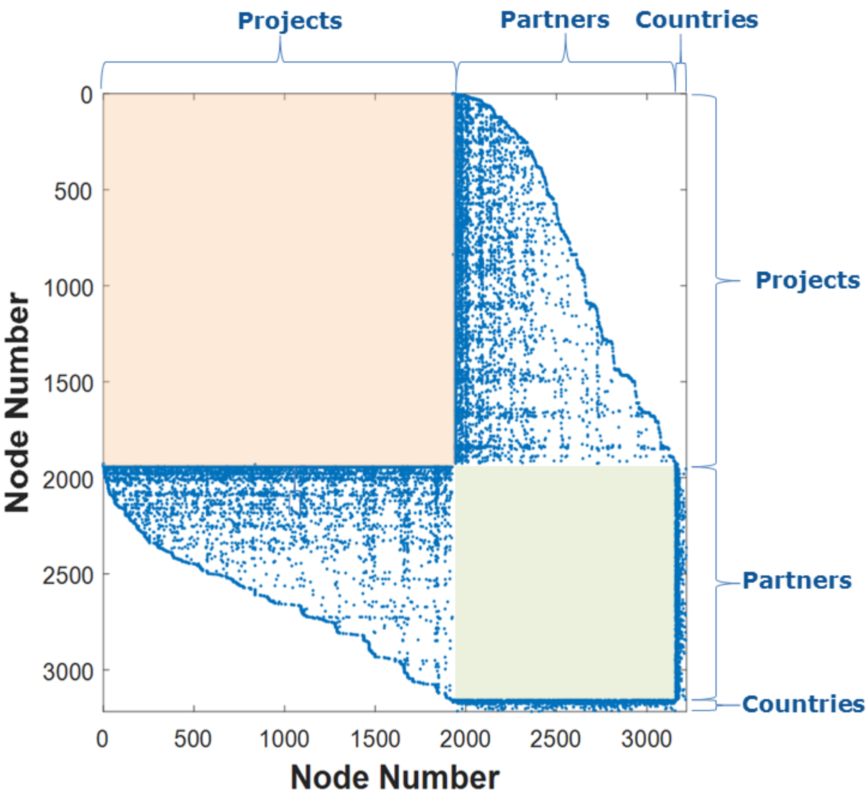


Figure 2 - Symmetric adjacency matrix of Projects-Partners-Countries network.

Original text:
Is Quantum Chaos quantum? Electron Spin is quantum!

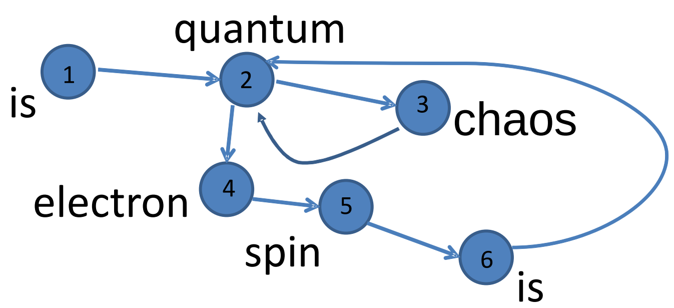
Parsed text:
is quantum chaos quantum electron spin is quantum

Word cardinality index sequence:
{1,2,3,2,4,5,6,2}

Edge Sequence:

From Node	To Node
1	2
2	3
3	2
2	4
4	5
5	6
6	2

The word cardinality graph.



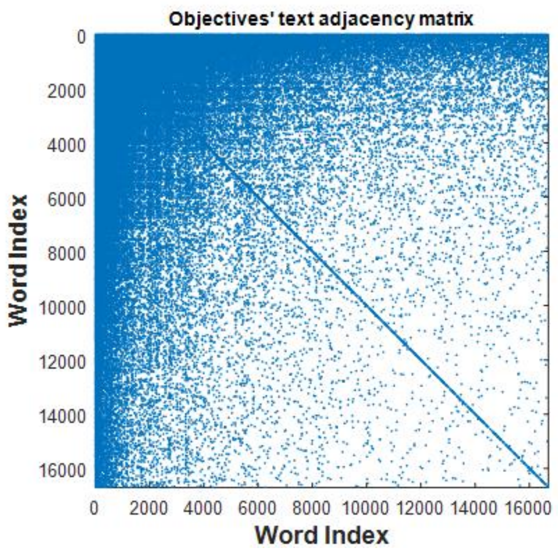


Figure 3 - A toy example of the construction of the graph adjacency matrix of a short text (top), and the adjacency matrix for the parsed text (bottom frame).

THE SEMANTIC NETWORK OF THE OBJECTIVES' TEXTS

Prior to the analysis the text corpus was parsed as follows: the character set consists solely of lower-case Latin letters and numbers; no punctuation, exclamation, question marks etc.; no separation from one project objective to another; no correction for typographical errors or standardization of hyphens, suffixes or prefixes; no homogenization between US and UK English spelling; no diacritics; no decimal points for numbers (substituted by blank). We comment on the impact of parsing on data interpretation in subsequent chapters. The text corpus compiled from the 1925 Objectives' texts generated 510925 'words' which were concatenated and ordered sequentially with the project time-line. The word cardinality—or vocabulary of distinct word items—was found to be 16703.

The frequency and appearance rate of the quantum-related words is discussed in the results and analysis section below, as is the semantic interpretation of the word '*quantum*' with the noun words it adjectivises, such as *quantum chaos,* as shown in Figure 1. Using the text corpus time series we constructed a 510295x510295 word adjacency matrix based on the method shown in Figure 3 as follows: first a cardinality number is assigned to each word on a first-come-first-serve basis; the cardinality number becomes the node number; two consecutive nodes are linked with value 1; whenever two consecutive nodes repeat, another 1 is added to their connectivity link count. The resultant matrix is weighted and directed.

3 RESULTS AND ANALYSIS

The analysis is divided as follows:

- Project filtering based on semantic analysis of projects' objectives.
- Correlation of funding to QT semantics.
- Overview of funding and participation rates by Projects, Partners and Countries

SEMANTIC ANALYSIS OF PROJECTS' OBJECTIVES TEXT

We abstracted the cardinal words from the Objectives texts corpus in the manner shown in Figure 3. The cardinal word *quantum* appears early in the first Objectives text at position index 11, the other 16702 cardinal words (vocabulary) appear according to the distribution shown in Figure 4. Herdan-Heaps curves are of the form of $\boldsymbol{H} = \alpha \times \boldsymbol{n}^{\beta}$ (Gerlach and Altmann, 2014), where α, β are constants and $\boldsymbol{n}$ is the number of items in the corpus. The trivial case $\alpha = 1$, $\beta = 1$ (the 45 degree slope) states that every element in a document—or some other cohort—is distinct and not repeated. Given a finite vocabulary and that no text corpus distribution can exceed the 1:1 slope (i.e. the cardinality number cannot exceed the set size), the slope of the Herdan-Heaps curve should nowhere exceed 1, hence $\boldsymbol{H}' = \alpha \times \beta \times \boldsymbol{n}^{(\beta-1)} \leq 1$ and $\lim_{\boldsymbol{n}\to\infty} \boldsymbol{H}' = 0$; however, it is not uncommon to see examples where, with the intent of showing an overall fit to empirical data, this criterion is violated in the first part of the curve, just as we have done for this text corpus putting $\alpha = 45, \beta = 0.45$ in Figure 4. Herdan-Heaps curves can also be used as a measure of innovation processes (Tria et al., 2018); hence it can also be applied to the partner participation rates as we shall show in subsequent sections.

Whereas all the Objectives texts include the word *quantum*, it may not apply in the technical or scientific sense we seek. To uncover the semantic meaning we look for syntactic two-word combinations where *quantum* acts as an adjective, e.g., *quantum computing*. We found 688 types of quantum-word combinations for a total of 7511 occurrences, of which the two-hundred most frequent, shown in Table 1, account for 6705 cases. The combinations provide what appears to be a comprehensive overview of a wide range of scientific and technical disciplines dealing with quantum mechanics: from *quantum information* (497 appearances) to *quantum molecular* (appears 4 times). In some cases the elimination of punctuation marks during the parsing process, especially for hyphenation, generate some combinations that, at first glance, may seem odd; thus we note that the prefix *many* (93 occurrences) refers almost exclusively (91 times) to *many-body*; *monte (*19 occurrences) refers always to *Monte Carlo*; the prefix *non* (17) mostly as *non-demolition* but also as *non-destruction non-locality*; *electro* (7) as in *electro-dynamics/optics; nano* (6), such as, *nano-electronics and nano-photonics.*

Not included in this table but still QT-relevant are a host of rare combinations (<4 occurrences), such as *quantum corrals, quantum bath,* quantum *knizhnik* (as in Knizhnik Zamolodchikov Equation), or *quantum espresso* (an open-source software based on quantum density functional theory). Another set of infrequent words concerns those that are either typos or misspellings, such as (sic) *sytems*, *noncommutativy, indeterministic, infromation*, for example.

The appearance indices of these QT-relevant quantum-word binaries identifies the position where such terms appear in the text time series; from these we calculate the number of words separating any two *quantum-word* combinations. In Figure 5 (top), as expected, the appearance indices increase progressively from the beginning till the end of the 510295-word objectives corpus. The distribution of intervals between two-word binaries is shown in in Figure 5 (centre) and the corresponding histogram in Figure 5 (bottom) suggests that the majority are well below 300 words—corresponding to the circa 2000 character limit requested in the project submission forms. In conclusion, the frequency rate and semantic clustering of quantum word binaries lends credence to the assumption that the major part of the projects we have extracted from the CORDIS data base appear, for the most part, to be significantly relevant to the field of quantum mechanics and directly related areas of particle physics, astronomy, cosmology, and other scientific fields where QT is of interest.

The two-hundred most common quantum binaries identified in Table 1, reflect basic research fields cited by the QTF. The ranking starts with *quantum information, quantum systems, quantum dots and quantum mechanics*. However, some word inflections may be combined, thus for example, *computing, computation, computer, computers* and *computational* would accrue 430 occurrences; *dots* and *dot* (360); *mechanics and mechanical* (348); *optics* and *optical* (259); *state* and *states* (197); *simulation, simulators and simulations* (174), are some of the most noteworthy cases; however, these amalgamations would change the order only moderately as these cases are already high up the ranking list.

Consequently, certain terms targeted in the QTF manifesto such as *computation* and *simulation,* as mentioned above, and *communication(s)* (99) are high up the ranking; but others such as, metrology (39), *sensing and sensor(s)* (44) less so. Engineering (25), occupies a rather modest position in the ranking, perhaps reflecting a lack of interaction with that community, or that research is still too far away from realistic engineering site applications.

Although the occurrence rate of these subject areas provides an indication of the popularity of the subject matter, what is perhaps more telling is to quantify the funding associated to each field or grouping. We will deal with this in a subsequent section.

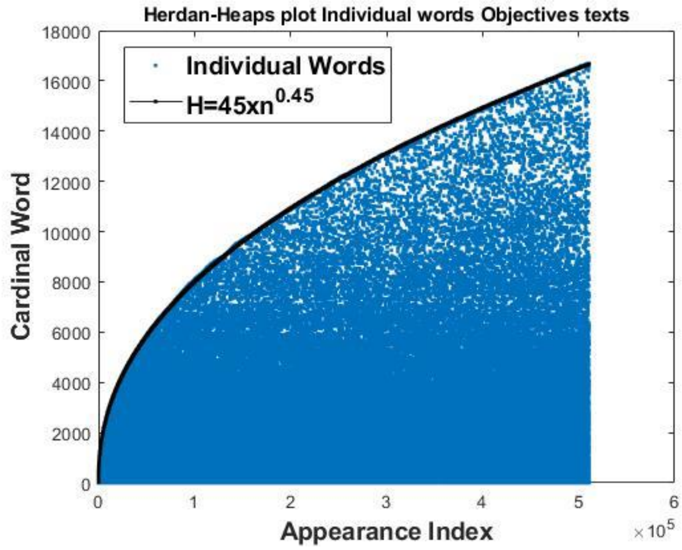


Figure 4 Herdan-Heaps curve for objectives text

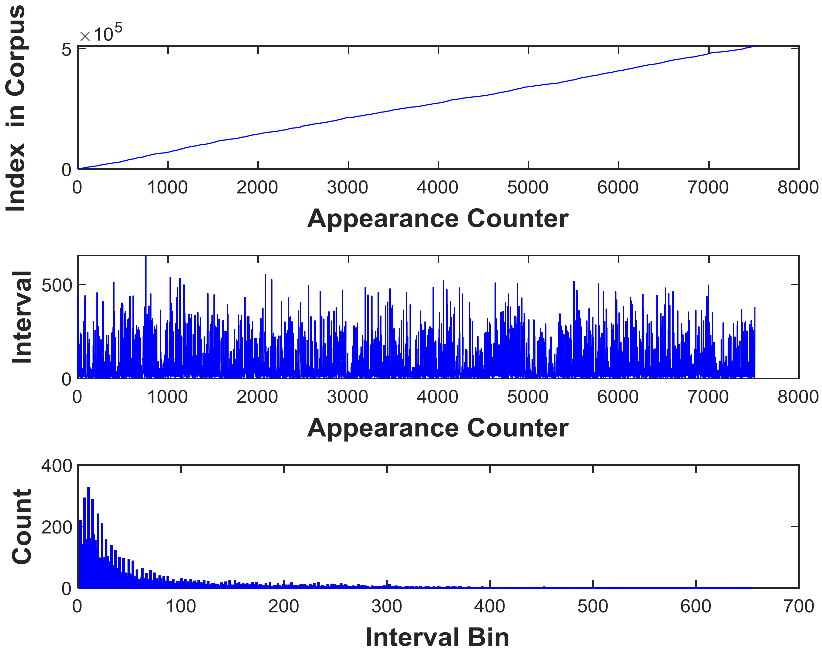


Figure 5 - Appearance indices, intervals and frequency counts of quantum-{word} binaries in the corpus of Objectives texts.

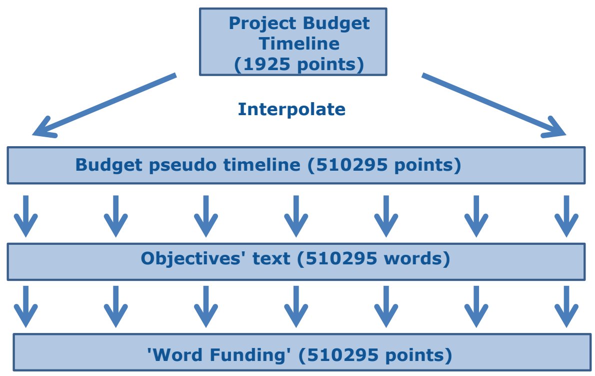


Figure 6 - Schematic for generating word-funding data file.

Table 1. - List of most frequent combinations of the form *'quantum{ word}'*. The numeric value on the left column of each word indicates the number of times the combination appears in the corpus; thus. *'quantum information'* appeared 497 times, *quantum molecular* 4 times. Note: verbatim spelling (UK versus US English), typos and closely-related or inflected words have been maintained, thus *'quantum dots'* and *'quantum dot'*; *'quantum mechanics' and ' quantum mechanical'*; *quantum tunneling and quantum tunneling*, etc. Some grammatical forms for linking complements of *quantum*, such as conjunctions and prepositions are included and highlighted for reference.

497	information	62	technology	37	groups	23	circuits	14	interfaces	10	degeneracy	7	features	5	physical
286	systems	61	devices	37	network	23	interference	14	processor	10	cosmology	7	radiation	5	domain
248	dots	59	simulators	36	***and***	21	coherent	14	key	10	chromo	7	channels	5	design
213	optics	57	dynamics	36	bits	21	sensing	14	criticality	10	superposition	7	degrees	5	detectors
201	mechanics	56	matter	34	**leap**	21	photonics	13	random	10	internet	7	electro	5	ict
172	field	56	correlations	34	properties	19	logic	13	vacuum	9	processes	7	metamaterials	5	foundations
172	computing	52	electrodynamics	33	gas	19	ground	13	tunneling	9	processing	6	computational	5	tunnelling
147	mechanical	51	computer	33	cryptography	19	photonic	13	statistics	9	point	6	models	5	algorithm
131	gravity	51	cascade	32	nature	19	well	13	corrections	9	teleportation	6	calculations	5	spintronics
129	states	48	coherence	31	algorithms	19	communications	12	measurements	9	resources	6	space	5	correlation
127	computation	48	networks	30	transport	19	monte(carlo)*	12	electronics	8	***to***	6	nano	5	mixtures
123	technologies	48	phases	30	simulations	18	noise	12	behaviour	8	structure	6	sensor	5	spacetime
119	physics	47	chemical	29	materials	18	yield	12	repeater	8	classical	6	behavior	5	plasmas
112	dot	46	level	29	light	18	chaos	11	structures	8	electronic	6	protocols	5	superpositions
93 (91)*	many (body)*	46	optical	29	gates	17	non	11	aspects	8	applications	6	yields	5	gravitational
86	effects	46	phenomena	28	confinement	17	world	11	degenerate	8	optomechanics	6	microwave	5	oscillations
85	simulation	44	regime	27	efficiency	17	science	11	bit	8	experiments	6	black	5	shannon
80	communication	44	system	26	emitters	17	sensors	11	measurement	8	magnets	6	walks	5	coherences
77	hall	43	phase	26	critical	17	repeaters	11	gauge	8	revolution	6	theories	5	affine
76	chemistry	41	memories	25	enhanced	17	fluids	11	plasmonics	8	feedback	6	probability	4	***in***
74	computers	40	entanglement	25	limited	17	wells	10	limits	8	efficiencies	6	enabled	4	effect
69	gases	40	memory	25	engineering	16	operations	10	device	8	bus	6	dash	4	dynamical
68	state	39	spin	25	fluctuations	16	magnetism	10	fields	8	flagship	5	***of***	4	interface
67	theory	39	metrology	25	limit	15	processors	10	error	7	numbers	5	architectures	4	molecular
64	control	39	chromodynamics	25	simulator	15	particles	10	thermodynamics	7	atom	5	nuclear	4	based

Table 2 - Cumulative 'funding' associated to most frequent common *quantum{word}* combinations rounded to nearest *K€*

2177	information	338	gravity	182	spin	124	simulator	72	processing	47	magnets	32	plasmonics	19	computational
1253	dots	316	hall	180	entanglement	121	engineering	69	criticality	45	effect	32	design	19	protocols
1126	systems	303	control	178	regime	114	enhanced	69	operations	44	electronic	32	black	18	physical
1041	mechanics	298	effects	177	gas	111	science	68	revolution	43	resources	32	calculations	18	affine
964	optics	289	theory	176	efficiency	110	sensors	67	chaos	42	metamaterials	31	ict	17	numbers
877	computing	287	electrodynamics	175	correlations	109	limited	66	particles	42	coherences	30	error	17	probability
782	technologies	274	dynamics	163	metrology	108	critical	64	bit	41	classical	30	theories	17	in
628	physics	271	phenomena	156	limit	101	photonic	62	vacuum	40	spintronics	30	oscillations	16	channels
619	simulation	248	gases	155	memories	100	memory	62	behaviour	40	point	30	features	14	algorithm
572	states	239	network	153	simulations	98	gates	60	gauge	38	limits	29	yield	14	structure
565	mechanical	235	internet	150	light	98	enabled	59	superposition	38	feedback	28	detectors	14	applications
560	field	235	networks	149	coherent	98	world	58	nano	38	to	28	structures	14	nuclear
559	communication	230	phases	146	emitters	97	ground	58	fluctuations	37	corrections	27	dash	13	models
510	dot	227	sensing	144	nature	95	transport	58	degrees	37	walks	27	thermodynamics	13	gravitational
484	cascade	227	coherence	143	chromodynamics	95	photonics	58	flagship	37	measurement	26	degeneracy	13	mixtures
475	computation	225	level	142	interference	94	logic	57	teleportation	36	tunneling	26	molecular	13	optomechanics
409	matter	225	computer	142	interfaces	92	sensor	57	experiments	35	electro	26	cosmology	12	interface
386	leap	219	materials	142	well	92	groups	55	processes	35	device	25	domain	11	dynamical
384	devices	207	optical	139	repeaters	88	wells	53	repeater	34	noise	22	of	10	atom
379	computers	204	bits	139	communications	87	confinement	53	degenerate	34	key	21	space	9	radiation
369	technology	200	processors	134	and	86	electronics	53	random	34	behavior	21	yields	9	based
363	state	198	system	130	algorithms	84	chromo	52	magnetism	34	aspects	21	shannon	3	foundations
347	many (body*)	193	properties	127	circuits	79	processor	51	non	33	architectures	21	fields	3	spacetime
340	simulators	190	chemical	126	fluids	75	monte(carlo*)	49	microwave	33	efficiencies	20	bus	2	correlation
339	chemistry	184	phase	126	cryptography	72	superpositions	48	statistics	33	measurements	19	tunnelling	1	plasmas

CORRELATION OF FUNDING AND SEMANTICS

What is the association between the semantic meaning and funding? One approach is to generate a budget pseudo-time series of equal length to the 510295-word objectives text (see Figure 6). Each appearance of a word in a project's objectives is tallied by that project's budget and normalized to keep the interpolated data the same as the gross funding budget (2,495 M€) . From this word-funding time-series we can compute the cumulative funding measure of each of the 16703 cardinal words, and from these, the specific occurrences of quantum-word combinations.

Table 2 presents the accrued funding of the *quantum word* binaries of Table 1 (not computing any other combinations of the *word* within the text corpus).

At a first glance it can be seen that generic terms or aspects of quantum mechanics such as *quantum systems*, *dot(s), field, gravity, state(s)* etc. are high up on the list because they contribute to a broad area of possible applications such as those currently targeted by the QTF.

Compounding the inflected words for *computer,* their aggregate weighting factor is circa 2000K€ which would put it at the very top of the list—plus another 2100K€ if we factor in the semantically-related case of *quantum information*. Other key themes mentioned in the QTF that appear in this list is the *quantum simulation* group (circa 1200k€), the *metrology* and *sensor* grouping (circa 540k€) and *communication(s)* (circa 700k€). In contrast, we also note that more than 550 out of the total 688 quantum combinations have a global weighting less than 50K€; due either to a low occurrence frequency, participation in lower budget projects, or a combination of both.

To examine this effect, in Table 3 the same words are normalized and ranked by the relative number of appearances (refer to Table 1) ; the order now is noticeably different as some items are biased by their low appearance rate; for example, *quantum enabled* and *quantum internet* have high relative funding because they only occur 6 and 10 times respectively, and are mentioned in large-budget projects. Other research areas such as *quantum shannon* and *quantum nuclear* appear to associated to less attractive funding potential by more than an order of magnitude in relative terms.

From the two-hundred items above we extract a subset of the forty most commo*n*. For this particular subset we construct the quantum topics interrelation matrix represented by the weighted graph shown in Figure 7. The interrelation between quantum-noun combinations may be encountered, for example, when projects mention more than one quantum field or application. We have plotted their interconnections using the force graph-display option that clusters the nodes in accordance to the strength of their bonds (thickness of links).

The core of the graph, by definition, is dominated by *quantum* linked to all other nodes. Strong connections exist between these, such as with *quantum systems, physics, chemical, information*, and so on. Topics that are more loosely connected to the core lie on the periphery. The strength and direction of interconnections between the quantum themes highlights the manner in which they may be found within a project description; for example, *dots* has only in-degree connections whereas *dot* implies connections with other words such as *quantum dot devices* and *quantum dot technology.* It can be seen that even with a small 40-node graph it is difficult to visually discern the interconnections, yet this type of information can provide a more in-depth clustering of semantic meaning and relations between quantum technology topics. The full quantum-semantic network is much larger and complex.

Table 3 - Relative funding to most frequent *quantum{word}* combinations *normalised by appearance frequency* rounded to nearest K€

24	internet	7	flagship	6	magnets	5	computers	5	enhanced	4	in	3	device	3	degeneracy
16	enabled	7	electronics	6	bit	5	computing	5	optics	4	hall	3	gates	3	gravity
15	sensor	7	experiments	6	world	5	simulations	5	photonics	4	efficiencies	3	measurement	3	cosmology
14	superpositions	7	coherent	6	simulators	5	classical	5	nature	4	regime	3	magnetism	3	structures
13	processors	7	communication	6	properties	5	domain	5	system	4	random	3	field	3	memory
11	leap	7	architectures	6	bits	5	electro	5	entanglement	4	chemical	3	computational	2	groups
11	effect	7	science	6	behavior	5	dots	4	optical	4	systems	3	transport	2	bus
11	sensing	7	efficiency	6	processor	5	theories	4	chemistry	4	monte (carlo*)	3	protocols	2	numbers
10	interfaces	7	molecular	6	detectors	5	simulator	4	dash	4	tunnelling	3	interface	2	key
10	nano	6	sensors	6	emitters	5	logic	4	of	4	mechanical	3	correlations	2	fluctuations
9	cascade	6	network	6	circuits	5	criticality	4	repeater	4	limits	3	confinement	2	models
8	revolution	6	design	6	electrodynamics	5	level	4	states	4	cryptography	3	aspects	2	channels
8	chromo	6	teleportation	6	electronic	5	networks	4	point	4	memories	3	error	2	based
8	coherences	6	technologies	5	gauge	5	engineering	4	computer	4	chaos	3	non	2	fields
8	degrees	6	devices	5	gas	5	degenerate	4	particles	4	computation	3	plasmonics	2	noise
8	repeaters	6	limit	5	state	5	dynamics	4	information	4	many (body*)	3	algorithm	2	structure
8	microwave	6	ict	5	black	5	phases	4	limited	4	and	3	corrections	2	applications
8	spintronics	6	interference	5	calculations	5	vacuum	4	theory	4	chromodynamics	3	probability	2	optomechanics
8	processing	6	walks	5	photonic	5	feedback	4	operations	4	statistics	3	tunneling	2	yield
8	materials	6	processes	5	physics	5	to	4	phase	4	physical	3	nuclear	1	atom
7	well	6	oscillations	5	wells	5	resources	4	features	4	gases	3	dynamical	1	radiation
7	fluids	6	metamaterials	5	mechanics	5	control	4	shannon	4	space	3	measurements	1	foundations
7	communications	6	technology	5	light	5	coherence	4	algorithms	4	yields	3	gravitational	1	spacetime
7	matter	6	superposition	5	behaviour	5	spin	4	metrology	4	affine	3	thermodynamics	<1	correlation
7	simulation	6	phenomena	5	ground	5	dot	4	critical	3	effects	3	mixtures	<1	plasmas

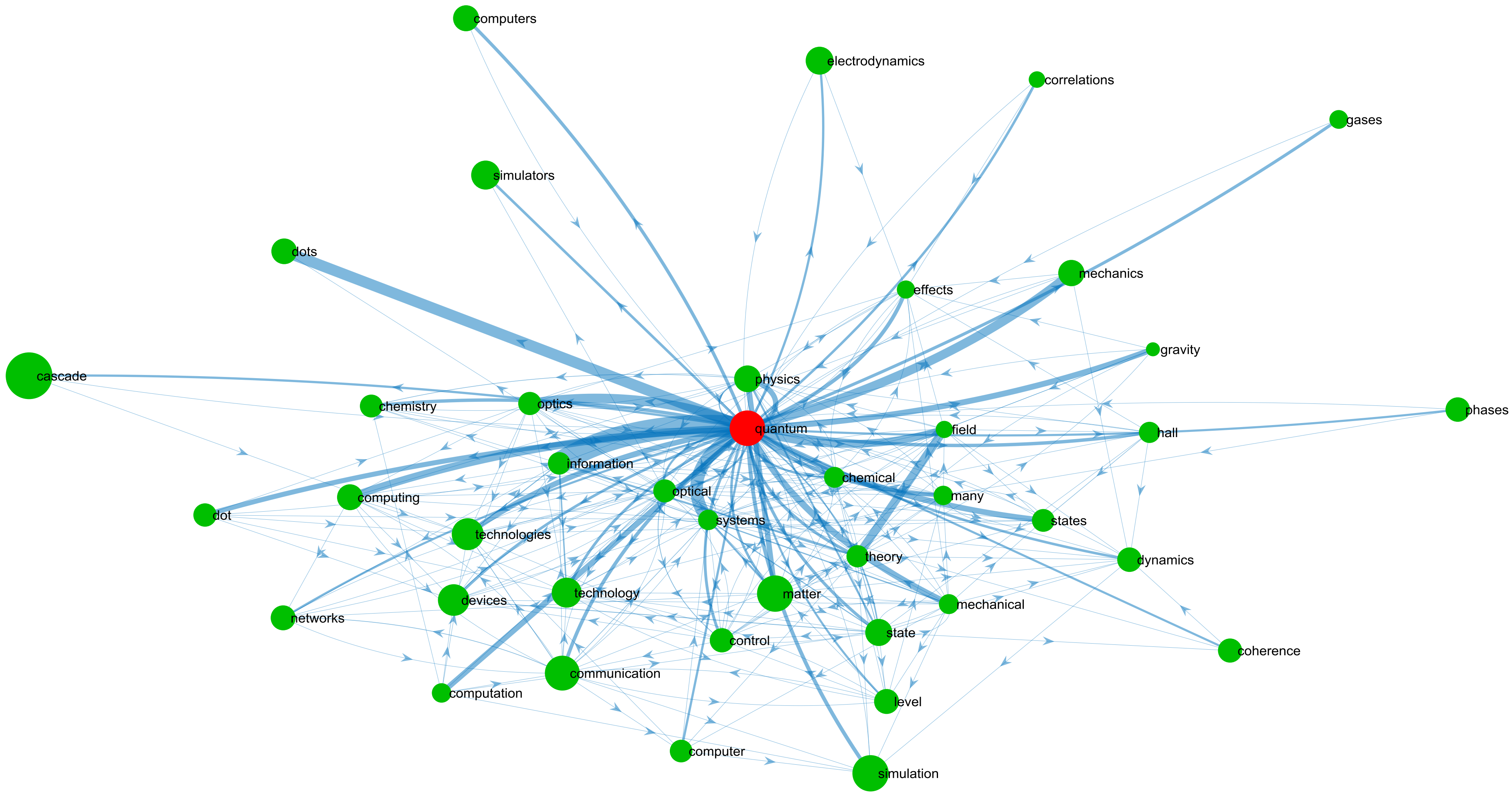


Figure 7 - **The directed graph showing the interrelation between top-forty quantum{word} binaries. The circle diameter is proportional to the funding measure normalised by relative appearance (see entry for respective words** in **Table 3. There are no major differences in scale between topics for this measure:** ***quantum cascade*** **is a factor of nearly four bigger than** ***quantum correlations*****,.**

PARTICIPATION TIME-RATES OF COUNTRIES AND PARTNERS

For open calls such as the EU framework programme, an important measure concerns the appearance rate of new partners and participant countries that join the funding schemes; it is to be presumed that the broader the variety and geographic distribution of the participants, the better the outreach. The data sets are constructed by cataloguing the identity labels of each partner and country along the projects timeline. This process generated two files of 6788 and 4680 data points for the projects and countries respectively (the latter is necessarily smaller because in any given project more than one partner may originate from the same country).

In Figure 8 we show the appearance time series of the distinct partners (top frame) and their associated countries (centre). The envelope of the curves represents the rate of growth of new entities into each cohort; this is analogous to the empirical Herdan-Heaps law in linguistics concerning vocabularies as a function of the document size; i.e. the rate at which new words appear in a text (also related to Zipfs law for word frequency).

Whereas the participant organizations number over one thousand, the participant countries number only 61. Nevertheless, there appear to be two distinct phases to the mode of country participation; in the first part there seems to be a solid rate of newcomer countries (fifty-seven in the first one-thousand appearances), thus with $\alpha = 1.75, \beta = 0.5$ (red line) we get a reasonable fit. Between points 1000 and 2000, the rate of new uptakes falls and gains only a few more participant countries, even if a substantial number of countries are still taking part. At around point 2000 there is a sudden drop, after which only 24 of the maximal set of 61 countries appear to participate; we fit this stage with $\alpha = 24, \beta \approx 0$ (black line). It is not yet clear to us how these sudden fluctuations may be due to changes in the funding programme, the economic climate at the time (post 2007), or regulations for participants; this would require a more extensive analysis of the data on funding topic identifiers which we leave for a subsequent publication.

Rather than just fitting the data to a single α, β value, we have calculated the slope of the envelope of the empirical Herdan-Heaps curves using discrete differentiation and smoothing to obtain the time varying slope $\boldsymbol{H}'(\alpha, \beta, \boldsymbol{n})$. We show this in Figure 8 (bottom frame) where, as expected, the rate of appearance of new partners is initially steep (~1); as recurrent partners reapply to new projects the slope flattens out to a banded region 0.6-0.7 (red line); this indicates that the rate of new partner entries increases throughout the period rather than a fast decline to zero. This could be interpreted as a positive outcome in policy terms as it appears that the EU programmes are reaching out to a larger number of institutions; however this does not change the fact that most of the funding goes to early-birds and, as we showed earlier, a relatively small number of partners. In contrast to the Partners curve, the slope of the Country participation starts off with a value of only 0.5, increases to 0.9 and then drops quickly to nearly zero (black line). The slope variations indicate that the country participation consisted of an initial reduced set, increased significantly shortly afterwards and then fell sharply towards a very low slope value. To some extent this fast overall decline is expected given the limited number of countries available; this is analogous to writing a 4860 word document with a vocabulary of 61 words, but what stands out is the highly non-monotonic behaviour; this is not so typical in Herdan-Heaps distributions and is perhaps indicative of strong disruptions that affected the participation of partners from some countries.

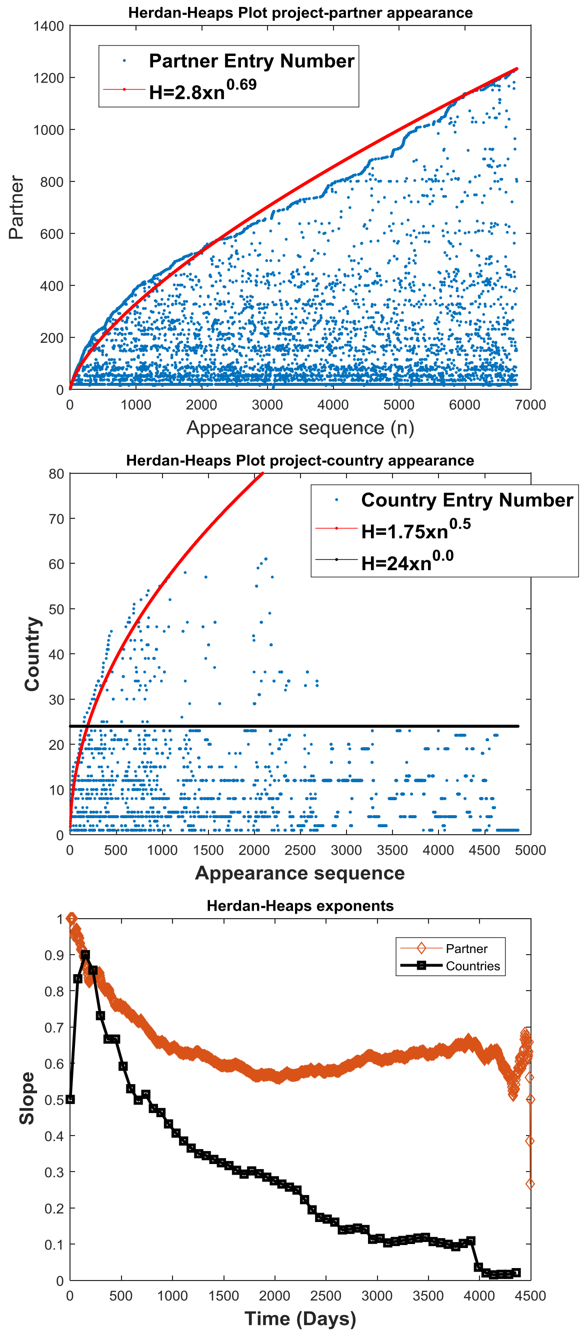


Figure 8 - The order of appearance of the project partners (top) and countries (centre) results in a Herdan-Heaps-like distribution. Of the 1230 partners, most appear early on, a select few of which keep reappearing frequently throughout the period 2007-2019. The dynamic variation of the Herdan-Heaps slope (bottom) over the duration of the appearance sequence is presented over the 4505 day duration of the dataset.

Commission Errors

Whereas the most frequent *quantum-word* binaries appear to have a bearing with QT, it is to be expected that some semantic combinations, and hence their associated projects, have no relevance whatsoever to QT. The best example of this type of commission error is the colloquial use of the term *quantum leap*; indeed we found that out of 34 such occurrences thirty-three appear in projects that have no bearing to QT. In addition we scanned one-hundred low incidence rate (<4) binaries and found a handful of commission error cases, namely *quantum advance (1 case), quantum intends (1 case),* and *quantum publishing (1 case).* We also examined combinations with grammatical forms such as conjunctions, prepositions or verb-forms (*and, to, of, in, or, for, is* etc.); here again, apart from a few exceptions such as *quantum of* (3 cases) and *quantum is (1 case)*, the remainder of cases were found to be QT-relevant—for example, *quantum {and/to/in/or} classical, quantum* {*and/to/in/o} statistical, computational, nonlinear, stochastic* amongst others.

We identified 36 projects (<2% of total) as being clear examples of commission errors which accounted to just under 100M€ (~ 4% of the total budget). A total of 92 partners (~ 7% of the total) participated exclusively in commission error projects reducing the overall participation from 1230 to 1138 partners. The chronology of commission error projects was found to be homogeneously distributed along the project-ensemble timeline, so we do not expect any major changes in the overall trends for project and partner Herdan-Heaps curves discussed earlier; however, their associated budgets were discounted from the partner and project funding presented below.

4 Overall view of funding

Figure 9 shows how the funding is spread out in terms of Projects and Partners. We have arranged the project data in chronological order based on the official project starting date (note that more than one project can start on the same day). We have also arranged the partners data set in pseudo-chronological order by noting the date of their first appearance as project participant; thus early bird partners appeared in the first projects.

As can be seen from the left frame on the top row of Figure 9, there is a wide spread of project funding, consistent with the fact that these range from small academic grants to large projects with consortia involving tens of partners and major research institutions. Nevertheless the cumulative funding—shown on the top right frame—increases progressively over the period studied, reaching circa 2,400 M€. To put this into context, the budget for FP7 (2007-2013) was circa 50,000 M€, and that for H2020 (2014-2020) allocated circa 70,000 M€.

This evolution is in marked contrast to the manner in which funding is accrued by the partners (lower two frames in Figure 9). As expected there is a wide range of funding budgets, whereby the major national research centres and universities accrue considerably more than less well-established and smaller institutions; but, interestingly, the largest budgets are associated to the early bird partners. This may imply that such institutions are well prepared and can commit planning and managerial resources to support their research groups' overheads when applying for the most ambitious and substantial project calls. The cumulative funding profile to partners—lower right frame— is therefore significantly different than that for projects, suggesting that those who started to participate early have probably done so due to the added advantage of expertise and corporate capacity.

In Figure 10 we show two equivalent forms of the cumulative budget evolution obtained by compiling the sum of the arcs of the weighted adjacency matrix of the project-partner-country connections. The sum of all the weights of the adjacency matrix (minus unitary partner-country counts) is equal to twice the budget (the matrix is symmetric so arcs are counted both ways from/to projects/partners); each section of the curve resembles the corresponding project-partner budgets shown in Figure 9, with each part amounting to approximately 2,400 M€ Euros. The modal form of the data (black line) is the cumulative sum of the eigenvalues of the Laplacian of the weighted adjacency matrix. The crossing points along the horizontal line mark the midpoints of each summation; the half-way point of the project-partner curve coincides with the point where the projects' budgets equal the partners'. In contrast, the modal distribution is markedly different; the sum of only the last two-hundred modes accounts for the same amount as the remaining three-thousand. Indeed, the forty highest modal contributions map to the partners with the highest budget which, together, total of the order of 1,200M€—or just under half of the total budget—the remainder of the 1138 QT-relevant grant applicants get the rest.

FUNDING TO PARTNERS

Table 4 summarizes some key aspects of the distribution of funds to the partners. It is to be expected that some organizations receive contributions consistent with their size (i.e. national centres or large universities); however, some smaller institutions seem to punch above their weight. Such a distribution of budget may recognize the need to diversify funding between both large and small institutions throughout Europe; however this, presumably, should not be at the expense of tangible quality output such as scientific publications, patents, proven industrial development, or currently imponderable potentials such as future job creation, security and cryptography. Another point to consider is whether success is solely down to technical and scientific capability rather than good networking and know-how of the funding mechanisms, especially given the importance that EU funds should be seen to reach out to those research groups where talent and diversification to some MS may be hampered by a lack of expertise in sourcing EU funding. We also note that there are of the order of 150 partners (mostly from non-EU, non-EEA countries) that received no EU-funding.

FUNDING TO MEMBER STATES AND OTHER NATIONS

It is not surprising to find that the lager MS (Germany, UK, France) or medium and smaller ones with active groups in quantum technologies (Netherlands, Austria, Denmark) do well, especially when they are long-standing members of the EU. Broadly speaking, the newer MS appear to be catching up with the funding rates compared to equivalent-sized veteran MS; however, there is a wide spread. For example, Spain (accession 1986) in comparison to Poland (accession 2004) appears to receive substantially more funding, whereas Czechia and Hungary (both acceded 2004) fair comparably with Greece (accession 1981) and Portugal (accession 1986) all of which have similar populations. At the other extreme we have Luxembourg and Malta, the two smallest states with comparable populations but with contrasting success rates. Admittedly, Croatia only acceded in 2013, but given its population of just over four million, it would seem that its institutions have yet to get earnestly involved in this branch of EU funding.

With regards to associate non MS states, which usually pay a financial contribution to the Union budget calculated on the basis of a ratio between its GDP and the sum of the MS, countries such as Switzerland and Israel do particularly well, perhaps reflecting the capacity and academic standing of their participant institutions.

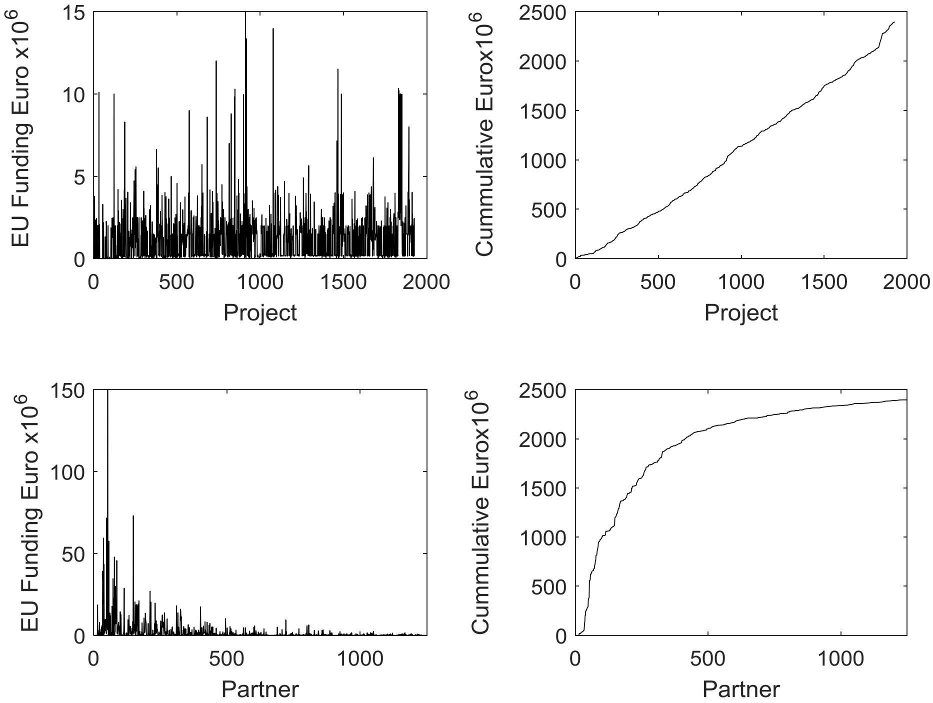


Figure 9 - **The EU funding shown in terms of project sequence for individual projects (top left) and the cumulative funding amount (top right).The distribution of individual funding to project partners varies considerably (bottom left), the cumulative amount received by all partners (bottom right) matches that generated by the projects. The project and partner indices are ordered in chronological appearance, with individual partners ordered by their first appearance in the projects sequence.**

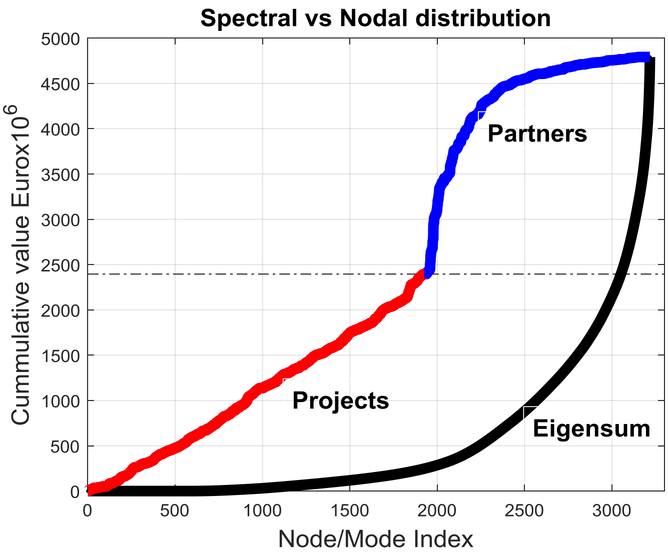


Figure 10 - **Comparison between nodal and modal distribution of weighted adjacency matrix and its associated Laplacian. Project indices—running from node 1 to 1925 in chronological order (red line)—are sum or arcs from projects to partners. Partners indices from 1926 to 3155 (blue line) indicate cumulative sum received by partners from projects, and are ordered by their first appearance in projects timeline.**

Table 4 - Cumulative funding for top forty project partners and all participant countries (EU MS highlighted in grey).

PARTNER	M€
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	**150.44**
EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	**73.05**
MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV	**71.65**
COMMISSARIAT A LENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	**59.40**
TECHNISCHE UNIVERSITEIT DELFT	**57.46**
THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	**47.81**
FUNDACIO INSTITUT DE CIENCIES FOTONIQUES	**45.67**
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	**43.46**
THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE	**39.16**
KOBENHAVNS UNIVERSITET	**34.60**
CONSIGLIO NAZIONALE DELLE RICERCHE	**33.49**
WEIZMANN INSTITUTE OF SCIENCE	**30.00**
AALTO KORKEAKOULUSAATIO SR	**28.76**
UNIVERSITY OF BRISTOL	**26.95**
THE HEBREW UNIVERSITY OF JERUSALEM	**26.13**
THE UNIVERSITY OF MANCHESTER	**22.37**
UNIVERSITEIT VAN AMSTERDAM	**21.08**
UNIVERSITAET ULM.	**20.40**
UNIVERSITAT WIEN	**20.29**
UNIVERSITAT BASEL	**20.07**
UNIVERSITAET INNSBRUCK	**19.73**
RUPRECHT-KARLS-UNIVERSITAET HEIDELBERG	**19.42**
UNIVERSITE DE GENEVE	**19.08**
CHALMERS TEKNISKA HOEGSKOLA AB	**19.06**
IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	**18.81**
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	**18.58**
TEL AVIV UNIVERSITY	**18.35**
LUDWIG-MAXIMILIANS-UNIVERSITAET MUENCHEN	**18.01**
TECHNISCHE UNIVERSITAET WIEN	**17.90**
JULIUS-MAXIMILIANS-UNIVERSITAT WURZBURG	**17.72**
UNIVERSITAET STUTTGART	**17.43**
UNIVERSITY COLLEGE LONDON	**17.19**
STICHTING KATHOLIEKE UNIVERSITEIT	**15.97**
OESTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN	**14.41**
UNIVERSIDAD AUTONOMA DE MADRID	**14.30**
KINGS COLLEGE LONDON	**13.82**
ISTITUTO NAZIONALE DI FISICA NUCLEARE	**13.73**
UNIVERSITY OF GLASGOW	**13.63**
IBM RESEARCH GMBH	**13.58**
TECHNION –ISRAEL INSTITUTE OF TECHNOLOGY	**13.30**

COUNTRY	M€
DE (Germany)	**475.62**
UK (United Kingdom)	**368.05**
FR (France)	**310.93**
CH (Switzerland)	**211.29**
NL (Netherlands)	**169.04**
IT (Italy)	**158.34**
ES (Spain)	**140.90**
IL (Israel)	**99.95**
AT(Austria)	**98.11**
DK (Denmark)	**67.93**
SE (Sweden)	**59.92**
FI (Finland)	**55.52**
BE (Belgium)	**42.40**
PL(Poland)	**20.85**
IE (Ireland)	**18.85**
NO (Norway)	**15.99**
EL (Greece)	**13.47**
CZ (Czech Republic)	**11.06**
PT (Portugal)	**9.31**
HU (Hungary)	**8.03**
LU (Luxembourg)	**5.01**
CY (Cyprus)	**4.26**
TR (Turkey)	**3.79**
LV (Latvia)	**3.67**
SI (Slovenia)	**3.41**
US (United Sates)	**2.90**
LT (Lithuania)	**2.89**
BG (Bulgaria)	**2.37**
SK (Slovakia)	**2.20**
RU (Russia)	**2.06**
RO (Romania)	**1.67**
EE (Estonia)	**0.97**
MT (Malta)	**0.78**
IS (Iceland)	**0.75**
AU (Australia)	**0.59**
LI (Liechtenstein)	**0.45**
BY (Belarus)	**0.45**
UA (Ukraine)	**0.39**
AM (Armenia)	**0.26**
HR (Croatia)	**0.26**

COUNTRY	M€
AR (Argentina)	**0.23**
BR (Brazil)	**0.23**
GE (Georgia)	**0.20**
SG (Singapore)	**0.10**
UZ (Uzbekistan)	**0.04**
ZA (South Africa)	**0.03**
IN (India)	**0.03**
CN (China)	**0**
JP (Japan)	**0**
CA (Canada)	**0**
MX (Mexico)	**0**
KR (south Korea)	**0**
NZ (New Zealand)	**0**
CO (Colombia)	**0**
HK (Hong Kong)	**0**
MA (Morocco)	**0**
MY (Malaysia)	**0**
PH (Philippines)	**0**
RS (Serbia)	**0**
TN (Tunisia)	**0**
TW (Taiwan)	**0**

These data reveal the highly complex nature of EU funding to the MS and in no way reflect the overall distribution across the board of the various EU funding vehicles; it may be the case that in certain other technical fields or EU programmes these trends may be quite different. Some of these divergences may be explained by the fact that some countries have one or more centres of excellence which tend to polarize the funding distributions; this is the case for some leading EU universities that attract more funding than the total budget of even some well-ranked countries.

Given these complexities, the answer to the question as to whether this funding configuration satisfies the aim of the R&D strategy at a European level cannot be answered solely by our observations above. Yet while our analysis is too coarse to deliver a solution on such policy questions, the panoramic view presented herein may set the scene for more targeted appraisals.

5 CONCLUSIONS

We analysed a compilation of EU-funded CORDIS projects with starting dates from Q2 2007 till Q3 2019 based on the search criteria that the word *quantum* appeared in their Objectives description text. To ascertain the technical relevance of this set, we conducted a semantic analysis of the concatenated Objectives texts. From a total of 1925 projects, 36 were found to be commission errors, whilst the remainder were deemed to have significant relevancy to quantum mechanics and its derivative technologies.

The analysis of the funding received by the projects partners and participating countries suggests that there is a clear trend whereby a reduced set of major organizations and leading universities (circa 40 entities) absorb a substantial part (circa 50%) of the funding. At a country level we have found that long-standing and large Member States receive the main share of funding. Notwithstanding, it is also evident that smaller States with established scientific tradition in QT do well in proportion to their population.

Whereas it could be plausible that newer MS would be lagging behind, there is a wide discrepancy within this group, with some being comparable to older MS on a pro-capita basis, whilst others far less so. Regarding non-EU countries there are two contrasting groups, in one we have countries from EEA and EU neighbourhood which outperform nearly all MS both in both absolute and pro-capita basis. A second group includes major world economies which participate with token amounts; added to these, other, less well-off, EU neighbourhood and transcontinental countries make up the list, receiving null or perfunctory sums.

Our analysis of the participation rates of institutions indicated that the rate at which new organisations join the cohort was quite high (sustained Herdan-Heaps slope of the order of 0.6-0.7). This implies that the funding programmes have attracted interest from an ever-growing set of new participant organisations. Nevertheless, the major part of the budget was taken up by a reduced set of actors; this might indicate that the involvement of smaller or less well-known institutions, especially for the major projects, may be conditioned by the strategies of the big players.

Whereas there were over one-thousand participant organizations, the small number of potential participant countries implies a strongly monotonically decreasing Herdan-Heaps slope. In practice it appears that the country involvement rate suffered a series of discontinuities; consequently, some countries ceased to take part. The implication is that after 2008-2009, perhaps coinciding with the financial crisis, the EU funding schemes or the international R&D policies of those countries changed considerably.

The semantic analysis of the projects' objectives texts not only confirmed the frequent use of generic terminology and core concepts of quantum mechanics but also highlighted the broad range of key enabling technologies such as *quantum dots*, *quantum optics,* and so forth. More difficult to assess is the eclectic range of putative applications that these research projects aim to achieve. By grouping inflections of certain words it was found that themes concerning *quantum computer(s)* and *quantum simulation* have attracted the most funding, more so if one attaches the occurrences of terms related to *quantum information* which is usually associated with computation and simulation. Based on this aggregation, our analysis suggests that the field of *quantum computers* and *information* is associated to projects that attracted more funding than other areas such as *quantum metrology* and *sensors,* or surprisingly, *quantum communications* and *cryptography*. The semantic analysis presented herein can be expanded to extract research trends and their respective funding by implementing a more refined parsing of the text; generating time-evolving semantic graphs, and the drawing out of topic cliques across the ensemble of projects.

Further work will include linking the projects identified in this report to discernibly quantifiable outputs like publications and patents, or concrete examples of technological advancement. Of particular interest, given its past and present importance, concerns the tracking of progress made in quantum computation measured against past predictions versus the current state of the art in the applied sciences and engineering.

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