TRUCE

Training and Research in Unconventional Computation in

**FP7 – ICT:**
**Coordinating Communities, Identifying new research topics for the FET Proactive Initiatives and Fostering Networking of National and Regional Programmes**

**Project no. 318235**

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# Work Package 1
# Roadmap Development

# D1.1
# Overview and consultation report

01 October 2013

Version 1.0

COOPERATION

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# Executive Summary

The brief of TRUCE project WP1 is: *To develop the first draft of a comprehensive roadmap document for UCOMP research and development in Europe and beyond, in order to identify new trends, challenges and opportunities*. This is to be achieved through a process of: information gathering, from the literature, from experts, and from the community; design and iterative drafting through consensus building; review and publication.

This first deliverable describes the initial information gathered, techniques to be used to gather further information from the community, and a draft structure and design.

# Contents

# Background and Scope

In TRUCE we are engaged in scientific *research* roadmapping. We have here a fundamental scientific domain – unconventional computing (UCOMP) – and we are mapping its scope and development.

This activity contrasts with conventional *technology* roadmapping.

> Technology roadmapping is driven by a need, not a solution. … It is a fundamentally different approach to start with a solution and look for needs. Technology roadmapping provides a way to identify, evaluate, and select technology alternatives that can be used to satisfy the need. [Garcia & Bray 1997]

The UCOMP domain certainly encompasses and is driving many novel and exciting implementation technologies, but they are only a part of the domain, not the entirety.

The TRUCE UCOMP research roadmap will provide the following (requirements adapted from [Sloman 2007]):

- A specification of the problem domain (scope)
- A breakdown into subdomains (structure)
- Potential routes to populating the domain (projects)

The process for developing the roadmap has the following components:

- Initial information gathering – literature, experts
- Structured community consultation, via questionnaire
- Roadmap design – skeleton structure
- Draft roadmap – initial population of skeleton
- Community review and critique of the draft
- Release roadmap – incorporating review inputs

# Initial information gathering

## Other roadmaps

The UCOMP roadmap is taking ideas and input on content and style from other research roadmaps, including:

- A Quantum Information Science and Technology Roadmap, v2.0, 2004, http://qist.lanl.gov
- QIPC: Quantum Information Processing and Communication, Strategic report on current status, visions and goals for research in Europe, v1.8, 2013, http://qurope.eu/content/Roadmap
- ChemBioIT: A Chemical and Biological Information Technology Science and Technology Roadmap, COBRA project, http://www.cobra-project.eu/roadmap.html

However, the key thing to note is that all these, despite themselves being broad and deep areas, are in fact subsets of the entire UCOMP domain. The TRUCE roadmap will not be able to cover the entire domain in the kind of detail seen in these doncuments.

## Major conferences

To develop contacts, and to help scope the field, two international conferences in the area of UCOMP were attended in summer 2013.

- UCNC 2013: 12th International Conference on Unconventional Computation and Natural C0mputation, Milan, Italy, July 2013
- ECAL 2013: 12th European Conference on Artificial Life, Taormina, Italy, September 2013
    - Location of the TRUCE Speculative Fiction Workshop

## Literature – journals and past conferences

Journals and conference proceeding publications provide an initial source of material to help scope the domain, and discover themes and subdomains.

Because of the broad and interdisciplinary nature of much UCOMP research, it can appear in widely scattered journals and conferences. So we start from a few well-targetted initial sources, from which further sources are then traced through references and citations in the usual manner.

Journals include

- Nature
- Science
- Artificial Life
- IEEE Transactions on Evolutionary Computation (IEEE-TEC)
- International Journal of Unconventional Computing (IJUC)
- Natural Computing
- Quantum Information & Computation (QIC)

Conference series include

- Unconventional Computation and Natural Computation (UCNS; previously Unconventional Computation, UC); published by Springer in LNCS series
    - Including co-located specialist workshops
- Synthesis and Simulation of Living Systems (ALife), and European Conference on Artificial Life (ECAL), alternate years; published variously in LNCS and by MIT Press
- NASA/ESA Conference on Adaptive Hardware and Systems (previously NASA-DoD Workshop on Evolvable Hardware)

On-line citation sources include

- DBLP
- PubMed
- Google Scholar

## Ngrams – a sanity check

In addition to targetted sources of literature, we performed a small "sanity check" on terminology, by searching for relevant ngrams via Google. See appendix, p.17.

This indicates that the "larger" classes of UCOMP are represented in the literature, but that smaller classes are not yet common.

## Structured community consultation

The initially gathered material has allowed a preliminary roadmap structure to be determined, and an online community consultation questionnaire to be designed. The TRUCE questionnaire will provide a major source of the detailed information needed to validate and augment this preliminary structure.

The questionnaire has been designed to gather information needed for the roadmap (and for other education TRUCE WPs). The design was aided by previous roadmap questionnaires, particularly COBRA's ChemBioIT. The information requested covers the following areas:

- UCOMP paradigms and technical domains
- Current and future status
- Current and future recourse needs
- Respondent demographics

The need for detailed information has resulted in a relatively long questionnaire (reproduced below in an appendix, p.21, for reference). We anticipate that the UCOMP community is willing to engage in this exercise.

The online version of questionnaire has been designed in Survey Monkey, and will be launched autumn 2013. Analysis of results will take place spring 2014. The online questionnaire can be accessed at https://www.surveymonkey.com/s/TRUCEroadmap.

## Roadmap draft design

UCOMP comprises several axes:

- *computational model*: the abstract computational concepts
- *substrate*: the physical realisation of the computational model in an unconventional computer, including the physical possibility of such a substrate
- *scalability*: the space/time/composition limits to larger versions, as a property of the model and substrate
- *programming*: the composition of the model concepts to perform a particular computation
- *applications*: the class of problems suited to a particular kind of unconventional computer
- others (TBC)

There are many ways for computation to be unconventional, for example, by not using the conventional substrate (of silicon transistors and logic gates), not using the conventional model (Turing/von Neumann), or not using the conventional programming approach (refinement) [Stepney et al. 2005]. It may be unconventional along only one axis (substrate say), but conventional along the other axes (Boolean logic implemented in an unconventional medium, say). Or it may be unconventional on multiple axes.

The UCOMP roadmap maps out the space of unconventionality, providing the **scope** of the domain. We consider "conventional computation" to occupy the point at the origin, and each unconventional axis to be a categorical, or at most a partially ordered, dimension.

Once having mapped the space, we can identify regions currently populated by research and results, and map out some potentially valuable, plausible, and feasible routes through and waypoints in the space.

Below is a preliminary mapping of the space of UCOMP, along several axes. This structure will be augmented by results from the questionnaire.

### Computational Substrates

Computation, including information, is physical [Landauer 1996], and must be realised in some physical substrate. The conventional substrate is the standard silicon chip, comprising CPU, RAM, and so on.

We can classify substrates by their physical properties

- silicon – transistors
    - single classical chip set
    - massive multi-core
    - GPU
    - FPGA
- quantum dots
    - for quantum computing
    - for programmable matter

- general purpose analogue media
  - Mills' "foam"
  - Lukasiewicz Logic Arrays
  - FPAA
- optical
  - classical optical computers
  - quantum-optics computers: photons as qubits
- NMR (nuclei, magnetic fields, radio frequency pulses)
  - for classical computing
  - for quantum computing
- "in materio" computing – complex physical materials
  - LCD
  - carbon nanotubes/amorphous substrates
  - graphene
  - non-linear magnetic materials
- historical special purpose mechanical analogue devices
  - orrery
  - tide calculator
  - mechanical calculators
    - early curve integrators
    - rod/gear integrators
    - clockwork difference/analytical engine
- chemical computing
  - reactions – R/D systems
  - field computing
- biomolecules
  - DNA/RNA
    - DNA as a construction material – tiles, etc
    - DNA as an information-carrying self-assembly material – generic circuits, etc
  - plasmids
- droplets
  - as a way of compartmentalising R/D
  - other computational processes
- cells
  - viruses, phages
  - single bacteria – synthetic biology
  - communicating bacteria
  - bacterial mats
- organisms
  - slime moulds
- theoretical/conceptual substrates (used to illustrate an unconventional principle, and explore limits, but never implemented in reality, beyond toy cases)
  - spaghetti – sorting
  - soap film/elastic band – minimisations/convex hull

    - gravity sorting
    - prism: light splitting for sorting
    - billiard ball computer
    - exotic – conjectured, but no ability to do yet
        - black hole/GR
        - branes
- hybrid systems that combine more than one substrate
    - composability of substrates
    - conventional computer plus UCOMP “compressor”
    - electronics + chemicals
    - neurons + silicon
    - droplets + R/D chemicals
    - chemical + bacteria (chemotaxis)
    - optical + bacteria (phototaxis)

## Computational Models

The conventional model is the underlying Turing model of computation (or any of the equivalent formulations) along with the von Neumann fetch/execute/store architectural realisation.

Computational hardware architecture may form a separate axis, or may be folded into computational model. Architectural realisations of unconventional models may form a “missing link” between the computational model and the substrate. This is currently an under-developed area, in need of population.

For each model, one important feature is the related complexity class hierarchy, and how the different models’ hierarchies fit together.

An important distinction is between universal and non-universal models – particularly some analogue devices are special purpose.

- digital/boolean
- quantum
    - data
        - discrete: qubits/qudits
        - continuous
    - model
        - circuit model
        - measurement model
        - adiabatic
        - quantum version of GPAC
- analogue
    - GPAC – General Purpose Analogue Computer
    - special purpose analogue devices
- real numbers
- fuzzy logic
- Cellular Automata

- neural
  - neural networks, of multiple subclasses
  - reservoir computing
- other bio-inspired models
- amorphous/field computing
- growth/construction models
- hybrid model composition

### Programming the substrate

The conventional model is (at least in principle) the "refinement/ compilation" paradigm, which at a high level goes from abstract specification to executable code via refinement, and at a low level goes from high level language to lower level language via compilation. The process is "correct" if it is "meaning preserving" (up to refinement of non-determinism), that is, both levels denote the same computation (commuting square).

Several stages might be conflated/distinguished differently

- building the computer
- programming the computer
  - configuring it to execute a specific computation
  - loading the program
    - one shot *v* multiple use
- providing the input data
- executing the program
- reading the output

## Programming paradigms

- classical programming
  - imperative, OO, functional, logic
- process algebras/concurrency
  - CSP/pi-calculus, POP, etc
  - relationship to various "brane" calculi
- reflective programming, self-modifying code
- probabilistic
  - gain the answer with a particular probability only
  - meta-heuristic –with no guarantee of success
    - bio-inspired search/optimisation – population based (EAs, ACO, PSO, AIS, …)
    - neural
    - reservoir
- quantum
  - circuit model
  - QGCL, Quipper
  - measurement model
- topological
  - GSL/MGS

    - this subsumes L-systems, P-systems, etc
    - growth/construction approach
- one shot devices
  - usually biological devices, fundamentally irreversible
  - tiling languages
- analogue devices
  - field computation
  - R/D systems
  - particles in chemical systems
- optical
  - fourier transforms, and other optical functions

## Current UCOMP research activity and results

The final roadmap will include a survey of the current state of UCOMP research. This will be populated from the questionnaire, literature surveys, etc

## Routes and waypoints

We will then be in a position to identify the relevant triples of Substrate/Model/Paradigm, and to identify gaps, for example, what is the programming paradigm for slime moulds.

The current draft map demonstrates that there is more progress on substrates than on models. There are many many substrates, but fewer models. This might be down to the fact that there are ultimately relatively few models of computation, yet specific sub-models still need to be identified, and attached to the relevant substrates. Unconventional programming paradigms, not surprisingly, are lagging well behind, for example, quantum computing is still mostly languishing at the gate and circuit level.

This preliminary map indicates that Routes are needed for

- filling gaps in the map – carving out new regions, eliminating unknowns
- combining existing regions – paths joining substrates to models, etc

This preliminary map indicates potential routes:

- develop models/languages for specific devices, then try to abstract more general models/programming paradigms from these
- exploit "search-based software engineering" techniques as a paradigm for programming/controlling unconventional substrates

The final roadmap will perform a systematic analysis of the maps, and define a range of suitable routes in detail.

## Summary and Conclusions

Initial work has resulted in

- identification of a draft structure for the domain map
- a design for the community questionnaire

The questionnaire will be launched imminently. The returns, combined with further literature reviews, and participant interviews, will be used to fully populate the domain map. The resultant roadmap will include an analysis of the domain, and an identification of missing regions where more research is needed.

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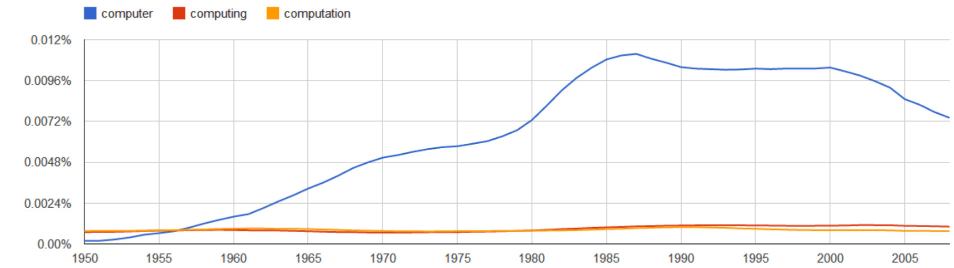
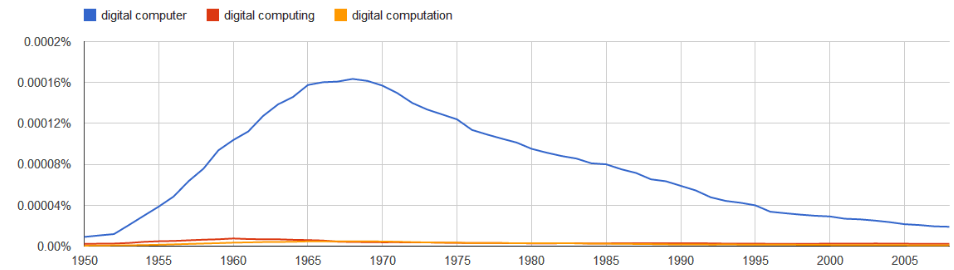
## Appendix 1: Google ngrams results

Google ngram results for year by year usage of particular computational paradigms in the English corpus of books from 1950–2008 (with a smoothing of 3). See [Michel et al 2011] and http://books.google.com/ngrams

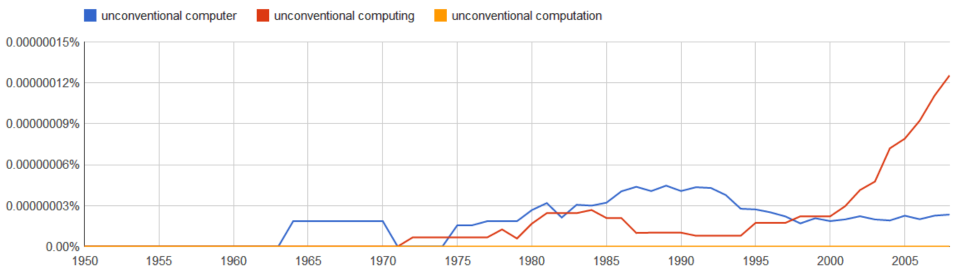
### computer, computing, computation, 1950–2008



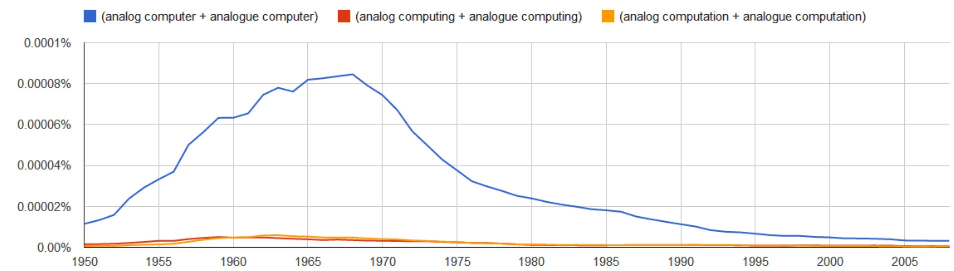

### digital computer, computing, computation, 1950–2008



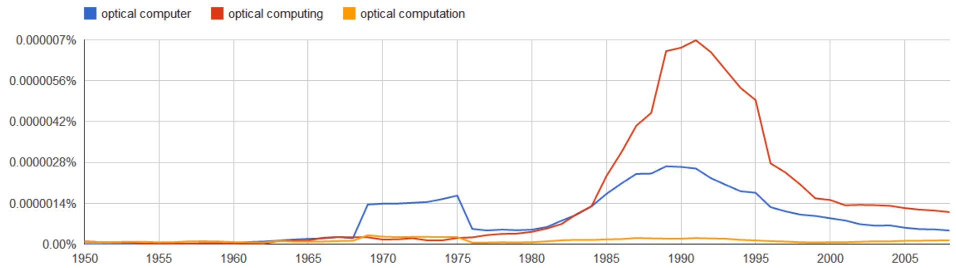

### unconventional computer, computing, computation, 1950–2008



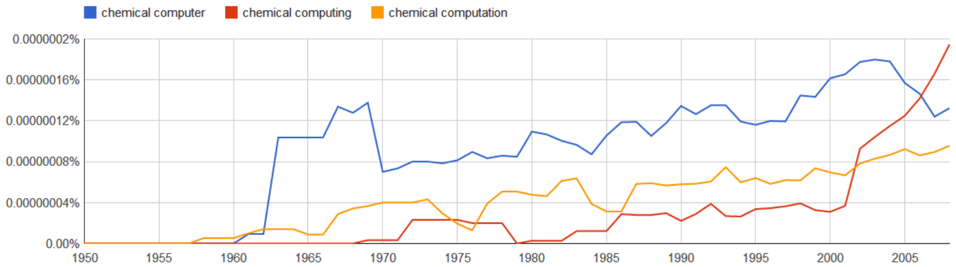

### analog(ue) computer, computing, computation, 1950–2008



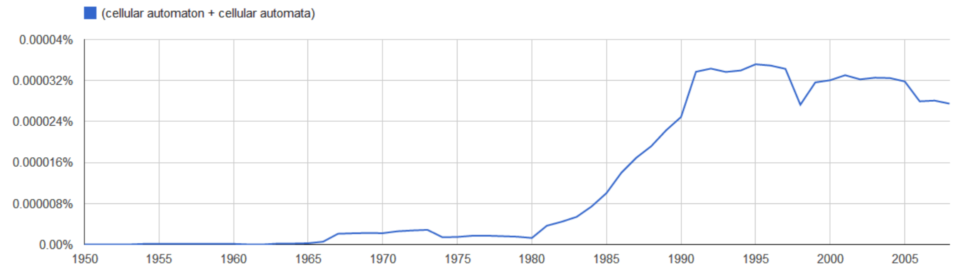
## optical computer, computing, computation, 1950–2008



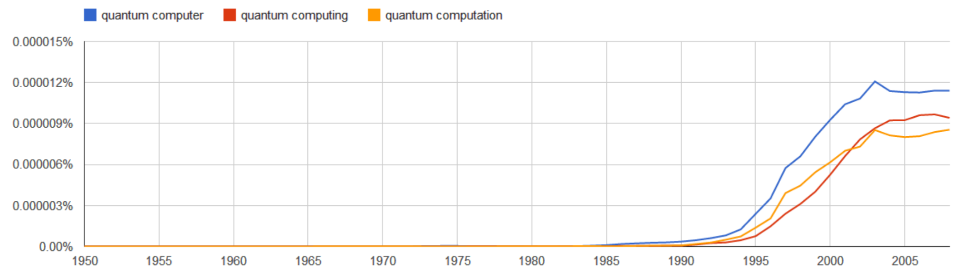

## chemical computer, computing, computation, 1950–2008



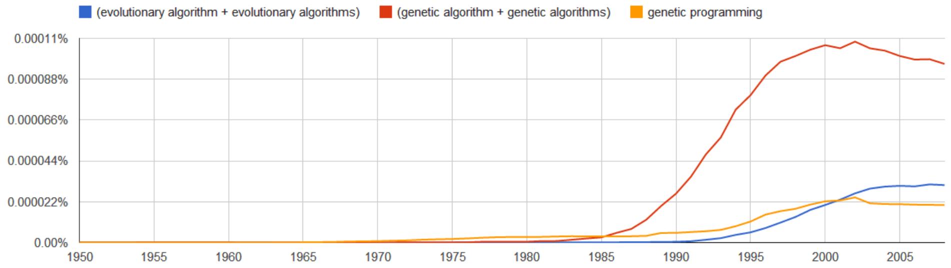

## cellular automaton/automata, 1950–2008



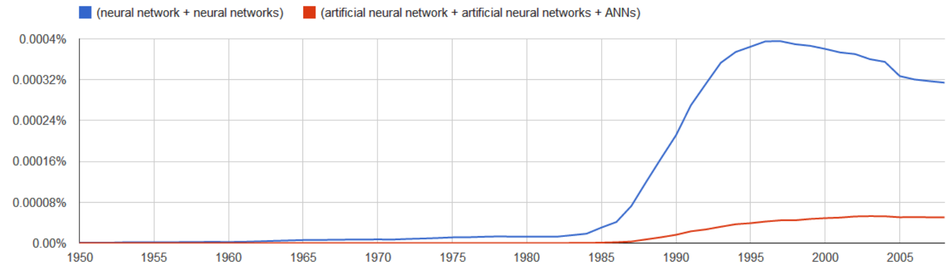

## quantum computer, computing, computation, 1950–2008



## evolutionary algorithm, genetic algorithm, genetic programming, 1950–2008



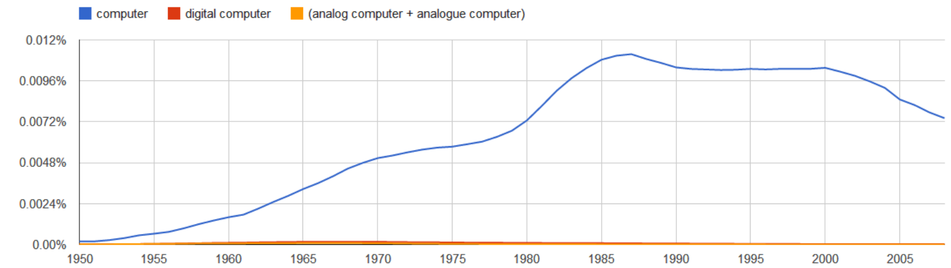

## neural network, artificial neural network, 1950–2008



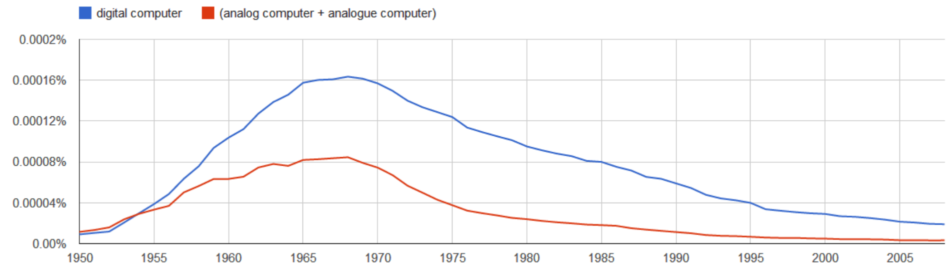

## bacterial, droplet, billiard ball, reservoir / computer, computing, computation, 1950–2008

No ngrams found. Note that this tool requires ngrams to occur in at least 40 books.

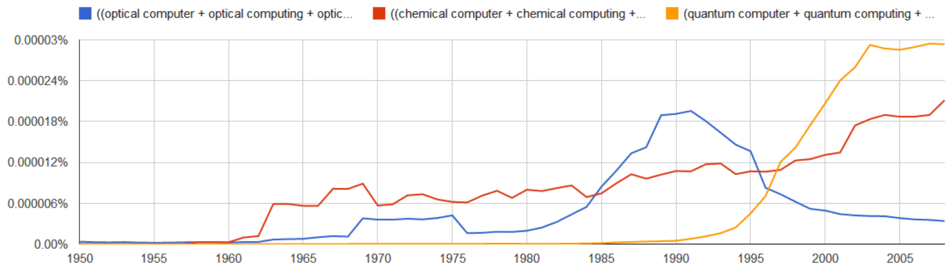
## computer, digital computer, analog(ue) computer, 1950–2008




## digital computer, analog(ue) computer, 1950–2008



## optical * 2, chemical * 50, quantum, 1950–2008



# Appendix 2: Questionnaire

The online version of questionnaire can be accessed at https://www.surveymonkey.com/s/TRUCEroadmap

## Introduction

Thank you for agreeing to complete the TRUCE Roadmap Questionnaire. Your answers will help to determine the desired shape and future of UCOMP research and development in Europe and beyond.

Please answer the following questions on unconventional computation (UCOMP) as fully as you wish. If some sections are not applicable to you research or interests, just write “N/A”. This survey should typically take between 15 and 30 minutes to complete. You can save your responses by page and come back to them later by clicking [Next]. Feel free to write detailed responses in the text boxes if you wish, or simply tick the radio buttons.

## 1. UCOMP paradigms

1.1. How would you define UCOMP?

1.2. What is your area(s) of UCOMP?

1.3. Please rate the following topics on this scale:

| | |
|---|---|
| 5 | Very unconventional |
| 3 | Mostly unconventional |
| 1 | Somewhat unconventional |
| −1 | Somewhat conventional |
| −3 | Mostly conventional |
| −5 | Very conventional |
| × | Not computation |
| ? | Don’t know |

← unconventional conventional →

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 3 | 1 | −1 | −3 | −5 | × | ? |

(Note, this list is not meant to be exhaustive, nor are all the items independent: the aim is to scope out where researchers feel the boundaries to the UCOMP territory are located.)

- Slime moulds solving mazes
- Evolutionary algorithms
- Adelman’s DNA algorithm

- Probabilistic algorithms
- GPGPUs
- FPGAs
- Decision making in organisations
- The market
- Bio-inspired algorithms
- Optical computing
- 3D printing
- Winfree et al's DNA tiling
- Simulated annealing
- L systems
- Fredkin/Toffoli billiard ball computer
- P systems
- Collective intelligence
- An orrery
- A slide rule
- An abacus
- Process algebras
- Membrane computing
- Quantum computing
- Artificial neural networks
- Hypercomputation
- Quantum communication
- GR space-time singularity
- Artificial life
- Analogue computing
- Systems biology
- A physical oracle
- Integrated information processing and material production
- Reaction-diffusion computing
- Reservoir computing

1.4. Give any classes of UCOMP missing from the above (and rate them)

## 2. UCOMP status

2.1. What UCOMP theory/implementation/application areas are *most* advanced?

2.2. What UCOMP theory/implementation/application areas are *least* advanced?

2.3. What UCOMP theory/implementation/application areas need *more* investment, and why?

2.4. What UCOMP theory/implementation/application areas need *less* investment, and why?

2.5. What areas will lead to commercial implementations in 5, 10, 20, 50 years?

2.6. What game changing UCOMP applications do you expect in 5, 10, 20, 50 years?

2.7. What are the key *scientific* (not financial!) barriers to further research/commercialisation?

## 3. UCOMP resources

3.1. What UCOMP Journals do you read/submit to?

3.2. What UCOMP conferences/workshops do you attend/submit/follow?

3.3. What UCOMP blogs/other media do you follow?

3.4. What UCOMP research resources are deficient/missing?

3.5. What UCOMP papers are seminal/influential/overlooked?

3.6. What UCOMP books have you read, would you recommend to grad students/to ugrad students?

3.7. What are the most notable/influential/overlooked UCOMP theories?

3.8. What are the most notable/influential/overlooked UCOMP implementations?

3.9. What are the most notable/influential/overlooked UCOMP applications?

3.10. What piece of equipment is most essential to your UCOMP research?

3.11. What material do you use to teach UCOMP, at what level?

3.12. What teaching resources need to be developed?

## 4. about you

4.1 Which country are you currently living in?

- [standard drop down list of all countries]

4.2 Gender

- Female
- Male
- Other
- Undisclosed

4.3 Age

- 15–25
- 26–35
- 36–45
- 46–55
- 56–65

- 66–70
- 70+
- Undisclosed

4.4 Affiliation (select all that are appropriate)

- Academia
- Industry
- Government
- Non-profit/third sector
- Other (please specify)

4.5 Position (select all that are appropriate)

- Taught student
- Research student
- Post-doc
- Lecturer/professor
- Researcher
- Manager
- Other (please specify)

4.6 Your work is mainly … (select all that are appropriate)

- Theoretical
- Experimental
- Computational Simulation
- Other (please specify)

4.7 Your domain/expertise is in …

- (Write in answer)

## 5. and finally

5.1. Are there any further comments you wish to make?

- (Write in answer)

Thank you for your time. Please SUBMIT your responses