Project Title:

What is Computation? (How) Does Nature Compute?

Integrating divergent and/or complementary views into a coherent whole.

Project Description: We are seeking support in organizing the 2008 Midwest NKS Conference whose theme makes up the title of this solicitation. The conference will be host to a most distinguished group of scientists (their names are listed below) upholding different views of a computable universe, from those supporting the thesis that Nature performs only digital (classical, Turing complete) computation and does it up to a maximal level, to those supporting the thesis of Nature as a quantum computer. Some argue very convincingly that the true nature of Nature can be only explained by a study of randomness. Randomness however preserves its mysterious reputation, and some of these authors espouse the view that randomness can be generated deterministically in the classical sense, while others claim the existence of "true" randomness from the principles underlying quantum mechanics as an indispensable premise for the complexity we see around us. This event will become the place of confluence in which all these views will be presented, discussed and analyzed by the guests and conference participants. After presenting their views during the first three days of the conference, the distinguished keynote speakers will then take part in a round table discussion on the topic.

Confirmed participants: [...]

Moderators will be: [...]

Significance should be assessed by looking at the topic in a 5-step historical context of its development:

1. The question of predictability has a long history in physics. From the days of Newton and Descartes physicists had constructed an increasingly elaborate view of the world. The entire universe was supposed to be a glorious clockwork, whose intricate workings scientists could hope to find out in limitless detail. By means of the laws of mechanics and gravity, of heat and light and magnetism, of gases and fluids and solids, every aspect of the material world could in principle be revealed as part of a vast, interconnected and strictly logical mechanism. Every physical cause generated some predictable effect; every observed effect could be traced to some unique and precise cause. The physicist's task was to trace out these links of cause-and-effect in perfect detail, thereby rendering the past understandable and the future predictable. And in the early 19th century, the classical deterministic laws of Isaac Newton led Pierre Simon de Laplace to believe that the future of the Universe could be determined forever. Then quantum mechanics came along and revolutionized our understanding of atomic and subatomic processes, by introducing probability and randomness as the very foundation of physics: in quantum mechanics one cannot predict more than the probability of occurrence of a particular event. More recently the modern study of nonlinear dynamics showed that even the classical physics of Newton had randomness and unpredictability at its core and chaos theory now makes the notions of randomness and unpredictability appear as a unifying principle rather than the pathological exception.

2. Mathematics has always been regarded as a bastion of certainty. Leibnitz explicitly emphasized this ideal: *"A method of solution is perfect if we can foresee from the start, and even prove, that following that method we shall attain our aim."* So, it is no wonder that 19th century mathematicians believed that mathematical truths could always be proved. In 1900, the mathematician David Hilbert gave a famous lecture in which he proposed a list of 23 problems as a challenge to the new century. It was the goal of Hilbert's program to put all of mathematics on a firm axiomatic basis, but according to Godel's incompleteness theorem every (sufficiently powerful) axiomatic system has undecidable formulas; and

so a final axiomatization of mathematics is impossible. As a result randomness lurks at the very heart of that most traditional branch of pure mathematics, number theory. Some mathematical facts are true for absolutely no reason. Although Godel was the first to devise his ingenious proof, couched in number theory, of what is called the incompleteness theorem, it was actually the Turing version of the theorem that was probably more fundamental and easier to understand. Turing used the language of the computer – the instructions, or program, that a computer needs to work out problems; and in some sense it's not a complete misrepresentation to say that Turing invented the computer in order to shed light on the philosophical question about the foundations of mathematics brought up by Hilbert.

3. The idea of a computational device was crystallized into a mathematical form as a *Turing machine* by Alan Turing in the 1930s. Richard Feynman pointed out in 1982 that it appears to be extremely difficult by using an ordinary computer to simulate efficiently how a quantum physical system evolves in time. He also demonstrated that, if we had a computer that runs according to the laws of quantum physics, then this simulation could be made efficiently. Thus, he actually suggested that a quantum computer could be essentially more efficient than any traditional one. Quantum mechanical computation models were also constructed by Benioff in 1982, but Deutsch argued that Benioff's model can be perfectly simulated by an ordinary computer. In 1985 in his notable paper, Deutsch was the first to establish a solid ground for the theory of quantum computation by introducing a fully quantum model for computation and giving the description of a *universal quantum computer*. Later, Deutsch also defined quantum networks. The construction of a *universal quantum Turing machine* was improved by Bernstein and Vazirani in 1997, where the authors show how to construct a universal quantum Turing machine capable of simulating any other quantum Turing machine in a polynomial way. After the pioneering work of David Deutsch, quantum computation still remained a marginal curiosity in the theory of computation until 1994, when Peter W. Shor introduced his celebrated quantum algorithms for factoring integers and extracting discrete logarithms in polynomial time. The importance of these algorithms is well-known, however the theory remains far more developed than the practice.

4. Algorithmic Information Theory (AIT, Chaitin) continues the work started by Godel and Turing and defines the information content of an object as the size of the smallest program that generates that object. The new information-theoretic viewpoint provided by AIT suggests that incompleteness is natural and pervasive and cannot be brushed away in our everyday mathematical work (and, indeed, AIT provides theoretical support for a quasi-empirical attitude to the foundations of mathematics). The program-size complexity measure of AIT is analogous to the Boltzmann entropy concept that plays a key role in statistical mechanics and from a physicist’s point of view a universal Turing machine is just a physical system with such a rich repertoire of possible behavior(s) that it can simulate any other physical system (thus, AIT is related to recent efforts to build a bridge between theoretical computer science and theoretical physics, especially in the study of complex physical systems such as those encountered in biology.) AIT gives a mathematical definition of what it means for a string of bits to be patternless, random, unstructured, typical. (And, as it turns out, most bit strings are algorithmically irreducible and therefore random.) AIT casts an entirely new light on the incompleteness phenomenon discovered by Godel by placing information-theoretic limits on the power of any formal axiomatic theory. In AIT we find Chaitin’s constant Omega, a real number whose digits are equidistributed and which is sometimes informally described as the probability that a random program will halt. Omega has the mathematical property that it is definable but not computable. Furthermore, it has been shown to be algorithmically incompressible (i.e., random). One consequence of this property is that, although mathematics is not arbitrary, it does contain irreducible facts/information (of which Omega is a prime example). Another consequence is that to the extent that the physical universe is anything like the abstract universe of mathematics, significant parts of it may turn out to be incomputable (in the Turing sense).

5. Rationalists like Leibnitz, Einstein and, more recently Stephen Wolfram have always rejected physical randomness, or *"contingent events,"* as Leibnitz called them, because they cannot be understood using reason. NKS is a methodology that borrows its name from the title of the 2002 Stephen Wolfram book, *A New Kind of Science*: *"The computer revolution has been fueled by our ability to have computers run specific programs built for particular tasks. But what if we were to explore the world of all possible programs?"* was Wolfram's breakthrough proposal. NKS then represents the unrestricted study of computation and so, like AIT, it too embraces a digital philosophy. Unlike AIT, however, NKS points out that short programs are capable of producing objects whose information content (in the classical sense) is maximal – in spite of their algorithmic information content being quite negligible (a short program is small). NKS further points out that, as a matter of fact, the vast majority of simple programs result in complex behavior so this is the rule rather than the exception. NKS consequently states its main thesis, the Principle of Computational Equivalence (PCE) that all simple programs whose behavior is not obviously simple are in fact at the same level of (maximal) complexity and that it is precisely behavior of this type that is responsible for the complexity we see around us. The PCE is essentially a generalization of the Church-Turing thesis and (if we want to oversimplify) it basically states that everything in nature is computation and that the threshold for universality is extremely low. The potential and implications appear to be groundbreaking, much like in quantum computation, only in a slightly different way. And just like in quantum computation the implications and perceived potential (of the theory) currently predominate the concrete, palpable results (in practice). *"One day,"* Wolfram says, *"the study of the computational world will no doubt be an established science, like physics, or chemistry, or mathematics. But today the exploration of the computational world still stands before us as a great frontier. With the potential not only to unlock some of the deepest questions in science, but also to define a whole new direction for technology."* It is therefore the purpose of this conference to try to open paths of communication, while attempting to identify possible points of contention, between NKS, AIT and the field of quantum computation. Each one of these fields taken separately makes perfectly valid and plausible claims—and with far reaching implications. However, the relative relationships between them continue to present the character of an open problem at this time.

Proceedings of the conference will be published in book form and may include contributions from: [...] who want (but may not be able) to participate in the conference.

Videos of all lectures and round tables will be posted on the conference website shortly after the conference. This is not the first conference of this kind we are organizing, and in this regard we will follow the model of our previous (and very successful) conference, the 2005 Midwest NKS Conference.

URLs for the websites of this and the previous conference:

- http://www.cs.indiana.edu/~dgerman/2005midwestNKSconference
- http://www.cs.indiana.edu/~dgerman/2008midwestNKSconference

Enduring impact: this conference represents an important assessment of our current understanding as well as a survey of promising directions of research for further advances in our understanding of ultimate reality.

- Is computation truly important, or is it just an artifact?
- Is anything else as important (or even more important) than computation?
- Is our universe computable? Is mathematics inevitable?
- Is quantum mechanics as we know it today definitive? Is quantum computation feasible?

- Is a systematic exploration of the computational universe practical (or will it ever be?)
- Is computation involved in perception?
- Is life, in any sense, computation—and if so, to what extent?

These are just some of the questions this conference (and the book that will follow it) will try to address directly. The members of the invited panel have made long-lasting contributions to their fields over the years and are uniquely equipped to participate in this interdisciplinary project addressing fundamental issues in biology, physics, mathematics and computer science. We plan to bring high-school students from all across Indiana to the conference, especially students that have distinguished themselves in the subjects mentioned above. The longest impact this conference will have will be in the hearts and minds of these young (and potential, prospective?) scientists. [...]

Relation to the Foundation's Mission, Core Themes and Funding Areas: The Foundation has served as a catalyst for discovery in areas engaging life's biggest questions. Our conference aims to do the same, thus advancing the mission of the Foundation. The proposal falls under the *"Natural Sciences"* theme, addressing questions on the laws of nature and the nature of the universe. Our conference brings together a panel with exceptional and established, distinguished scholarship in rigorous scientific research. The conference is an open-minded inquiry at the intersection of three cutting-edge directions of research with both practical and theoretical implications: quantum computation, algorithmic information theory and NKS. Together, these three areas have the potential to revolutionize any or all of the following domains: Biology, Chemistry, Computer Science, Earth Science, Engineering & Technology, Genetics, Mathematics, Neuroscience, and Physics as a whole. In its quest, and in its methods, the conference will be a true, honest, down to earth and entirely open debate, in consonance with (and actively engaging) the following core themes of the Foundation: creativity, emergence, future-mindedness, honesty, humility, infinity, and ultimate reality. The Socratic method starts with *"I know you won't believe me, but the highest form of Human Excellence is to question oneself and others."* In that respect our conference is a unique investment opportunity for the Foundation. Richard Hamming once said: *"One of the characteristics of successful scientists is: having courage."* But courage alone, although necessary, is not sufficient. *"Once you get your courage up and believe that you can do important problems, then you can. If you think you can't, almost surely you are not going to. [...] If you want to do great work, you clearly must work on important problems, and... you should have an idea. "* The combination of topics in our conference is unique—partly because there are mild (but healthy) tensions between each of the individual fields taken separately, which usually results in separate conferences on each individual topic. The probability for a groundbreaking discussion becomes considerable given that we have assembled a stellar panel of keynote speakers and moderators who can inspire and guide with unparalleled grace and integrity.

"Most people like to believe something is or is not true. Great scientists tolerate ambiguity very well. They believe the theory enough to go ahead; they doubt it enough to notice the errors and faults so they can step forward and create the new replacement theory. If you believe too much you'll never notice the flaws; if you doubt too much you won't get started. It requires a lovely balance. But most great scientists are well aware of why their theories are true and they are also well aware of some slight misfits which

don't quite fit and they don't forget it. [...] When you find apparent flaws you've got to be sensitive and keep track of those things, and keep an eye out for how they can be explained or how the theory can be changed to fit them. Those are often the great contributions. Great contributions are rarely done by adding another decimal place. It comes down to an emotional commitment. Most great scientists are completely committed to their problem. Those who don't become committed seldom produce outstanding, first-class work.“ (Richard Hamming)