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C. S. Peirce and Computation as Automatable Semiosis

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(This is a pre-publication draft; for reference only. Comments and discussion welcome.)

> A celebrated treatise [by Hobbes] is entitled *Logic, or Computation*, and although not all reasoning is computation, it is certainly true that numerical computation is reasoning. But calculating machines are in everyday use; and Babbage's analytical engine would perform considerable feats in mathematics. Other logical machines have been constructed. All those instruments perform inferences; and those inferences are subject to the rules of logic. -- C. S. Peirce, "Minute Logic" (1901)

> The stored-program computer, as conceived by Alan Turing and delivered by John von Neumann, broke the distinction between numbers that ***mean*** things and numbers that ***do*** things. Our universe would never be the same.
> --George Dyson, *Turing's Cathedral* (2012)

This paper is part a larger work in progress on computing, sign systems, symbolic cognition, and the history of technical mediation from a Peircean semiotic perspective. As a step in bridge-building between computational and humanistic disciplines, this paper will introduce a new method for a detailed redescription of computational processes as implementations of *automated semiosis* and of digital media artefacts as representations within the *continuum of technical mediation* in the cultural history of human sign systems.[1]

I'm proposing a synthesis of intersecting directions in research in cognitive science, linguistics, computational theory, semiotics, and philosophy of information that unify the humanistic disciplines with knowledge formation in technical and scientific fields around the key questions of human symbolic cognition, sign systems, meaning generation, and information representation in any physical or technical structure. Interpreting Peirce's later writings in this larger context, I argue that computation, software, and digital media are best understood as *artefacts of human symbolic cognition* and have thus emerged as cumulative outcomes of a long continuum of implementations for mediating human sign systems.

All evidence now indicates that symbolic cognition is the core *human operating system* (I call it OS Alpha, *OS A*), which human societies have extended in multiple physical substrates and technical mediations with complex histories of cumulative combinatorial development. Further, ongoing research in many sciences provides cross-domain confirmation for hypotheses for understanding human consciousness, cognition, and computation as kinds of information and sign-code processes writ large throughout organic and inorganic structures. In this emerging view, human semiosis (OS Alpha evidenced in generative sign actions) underlies the discoverability and interpretability of information structures in all systems within which we are observer-interpreters.

My argument is also framed by a specific definition of *semiotic technologies* as social-technical systems employing material-physical symbolic substrates as cognitive artefacts.[2] We have a long cumulative history of technologies developed for supporting meaning systems in our inherited technologies for writing, imposing images on material substrates, reproducing and storing all kinds of symbolic representation, sending and receiving symbolic expression in communication media, and in recent semiotic technologies for digital remediation and combining multiple levels of abstraction and materialization in automatable information processes. These material systems constitute a special class of technologies, *symbolic-cognitive technologies*, and have always had a special status in our larger social-technical system of artefacts, machines, and industrial products. S*ymbolic-cognitive technologies*, of course, require general technologies used in instrumental ways (e.g., electricity, developments in materials science, component and supporting technologies), and have been part of long histories of cross-domain developments, but semiotic technologies must be studied and explained with a specificity beyond general technologies and all other kinds of machines. Calling computers or communication devices with microprocessors and network connections "machines" only reifies them as black boxes and treats computing devices merely as empirical *facts* rather than *artefacts* that can be interpreted, explained, and understood on semiotic principles.

To reveal the deeper continuum leading to our current semiotic technologies, I will trace the trajectory of symbolic thought that enabled the designs for correlating electronics with symbolic values in our era, a trajectory that connects the ideas of Samuel Morse and C. S. Peirce to Alan Turing and Claude Shannon, and all the way through the recent development of pixel-mapped graphical computing interfaces for all sign systems in digital media.

I will be focusing on Peirce's work from the last productive decade of his life, 1902-1912, when he was working on his major synthesis of "logic as semeiotic." Over the past 4 years, I've been doing archival research on Peirce's unpublished papers from this period. I have discovered new sources for developing a more complete picture of Peirce's insights on semiotic technologies and the logic of signs and operations, which also strongly supports the extensibility of his semiotic philosophy and his integrated view of the sciences, logic, philosophy, and humanistic fields that have important consequences for our current moment. Had these writings been recovered and published earlier in the reception of Peirce in the 1930s-1960s, Peirce and semiotics in general would be in a very different position today.

For the scope of this introductory paper, I will focus on four related concepts in Peirce's theory that are extensible to the physical and symbolic architecture of computing systems and digital media:[3]

1) The material *structured substrate function* in any sign system: the necessity of structured physical-material-perceptible substrates with affordances for inferring significant features (sounds, substrates for visual representations, materials for 3D artefact, etc.). The substrate function is a necessary condition for signs and symbols to be instantiated as such, and thus forms a continuum across physical media at any historical moment of development.

Peirce re-described the necessary material-perceptible structures of signs in three phases of his philosophy, first as feature-bearing Representations, then as Representamens (whatever performs the function of representing) that supply percepts correlatable to objects and interpretants, and then simply as the material-perceptible feature-bearing component of signs, the technically mediated forms of which can produce actions and systemic agency. All sign systems are unified by requiring a structured, symbolically motivated, material *substrate* capable of eliciting percepts by sign-cognizers in a community. S*tructured semiosic substrates* are required for supporting feature extraction and pattern recognition that enable semiotic agents to "go beyond the information given" (Peirce and Bruner) by enacting the first level of correlations that enable us to convert percepts into signs. (The contemporary development of fields devoted to signal detection, feature extraction, and pattern recognition in information and computer sciences confirms the necessity of this structure.) The material sign substrate, which can be modelled as a stack of material-perceptible features enabling perceptible and phenomenologically based *percepts* to be interpreted as, or "resolve into," tokens (specific instances) of symbolic types (whether as sequential strings or compositional clusters).[4]

2) The function of indexical signs (indices) in the combined material-symbolic-cognitive processes of *semiosis* (sign actions as a dynamic processes over intervals of time) in the overall symbolic architecture of computation and digital media objects. Computation and digital media processing are designed to depend on many levels of indexical mappings and physical *retokenization* across substrates.

3) Extending Peirce's well-known Type/Token distinction (abstract forms generative of replicable material instances) as used in computation for ongoing *re-tokenization* of forms in and across physical substrates. The type/token distinction

and the materially correlated index provides a model for the decomposability and re-composability of triadic sign structures in digital electronic states, and for mapping pixel arrays to and from memory states.

4) Sign agency delegated to automating two classes of sign structures (symbols that *mean* and symbols that *perform operations*, data structures and program structures) in a common representational form (binary, base-2 number values correlated to electronic states) and internal substrate (digital electronics). The understanding and specification of different classes of signs and sign functions has a long history, which I cannot outline here, but the key to understanding automatable symbolic processes, as Peirce discovered, is seeing that *what can be represented as formally necessary* can, in principle, be automated. Mathematics and logic provide methods for generalization and abstraction of invariant patterns, we can formally designate symbols and operations in signs for meanings and signs for operations that yield necessary logical results within a formal sign system, and the merging of these in necessary processes for enacting interpretations and transformations across sign structures is the foundation or platform for *automatable semiosis*.

The explicit understanding of signs and operations was central to 19th century mathematics, especially as implemented by Boole and Babbage, and Peirce was a major contributor to the tradition of Boolean mathematical logic that Shannon, Turing and modern computational theory is founded on. As George Dyson described the ideas behind modern computing, "The stored-program computer, as conceived by Alan Turing and delivered by John von Neumann, broke the distinction between numbers that *mean* things and numbers that *do* things. Our universe would never be the same."[5]

The trajectory described by Dyson began in Peirce's era: an algebraic system for representing sign values and operations, and definitions for correlating sign meaning and sign actions or agency were at the center of Peirce's later semiotic philosophy, much of which was inspired by Boole's algebra of logic. In modern computation, binary numbers represented in symbol units can be assigned two functions: value-representing symbols (units of meaning representations) or operation-and-relation symbols (symbols representing rules and mathematical-logical functions, patterns of interpretation assigned to actions, transformation operations, over the value-representing symbols in the computing architecture). Computing, at whatever scale or degree of complexity, implements logical architectures for combining symbols that *mean* (hold values) and symbols that *do* (invoke actions and operations), both simultaneously communicated and differentiated throughout the same physical, electronic substrate.

C. S. Peirce is in the middle of the story of these foundational ideas, historically and intellectually. Peirce provides the most usefully heuristic and extensible set of terms and concepts for describing sign functions as *correlated material-cognitive processes* that occur as bundles of symbolic representations, operations, and time transitions, bundles which are themselves symbolically representable in physical media.[6] However, recovering Peirce's ideas from his final formulations and syntheses is not simply an archival or historical project: Peirce provides us with a rich and still unsurpassed vocabulary for describing the semiotic structure of computation and digital representation. As John Sowa, the CS pioneer who championed Peirce's logical graphs as models for knowledge representation put it, "Peirce improved on his successors."

We will begin with two exemplary cases in the foundations of electronic communication and in the proto-history of computing -- Samuel Morse's electromagnetic "system of signs" and C. S. Peirce's diagrams for electrical logic circuits using Boolean algebra -- and then consider Peirce's treatment of sign processes in a framework for understanding computation as a design for automatable semiosis. The proto-history of electronic computing began when electrical circuits were first conceived as structures for symbolic correlations—sign abstraction and retokenization (Morse) and relations in an algebra of logic (Peirce). The work and careers of Samuel Morse (1791-1872) and C. S. Peirce (1839-1914) span the great "century of invention" for the semiotic technologies that are still with us, and they represent important nodal points in the history of modern computing, nodal intersections with links to George Boole and Charles Babbage in England, to the developments in electronics by Claude Shannon, and to the traditions in logic and mathematics used by Alan Turing. Nearly everything we take for granted in modern telecommunications, computation, and semiotic technologies has foundations in this era.

On his return home to New York from Paris in 1832, the same year that Charles Babbage began designing his first Difference Engine, Samuel Morse was preoccupied by two concerns. He was carrying with him his famous metapainting of *The Gallery of the Louvre*, which he hoped would confirm his career as a history painter and mediator of European high culture, and he was also thinking about an idea for controlling an electrical circuit designed to represent a sign system for sending messages across any distance.[7] Morse began his career as a painter after graduating from Yale, and his knowledge of what was happening in the sciences, begun while he was a student, also made him fascinated about electricity and electromagnetism. On this now-famous ship voyage in 1832, Morse recounted how he first connected the ideas for his model of the electromagnetic telegraph [image of painting and text parallel]:

> [O]n my voyage from Europe, [I recalled] the electrical experiment of Franklin...in which experiment it was ascertained that the electricity

> traveled through the whole circuit in a time not appreciable, but apparently instantaneous. *It immediately occurred to me that, if the presence of electricity could be made VISIBLE in any desired part of this circuit, it would not be difficult to construct a SYSTEM OF SIGNS by which intelligence could be instantaneously transmitted.* The thought, thus conceived, took strong hold of my mind… and I planned a system of signs, and an apparatus to carry it into effect.[8] [Emphases as in original text]
> [Morse's biographer continues:]
> The spark shall be one sign; its absence another; the time of its absence another. Here are three signs to be combined into the representation of figures or letters. They can be made to form an alphabet. Words may thus be indicated. A telegraph, an instrument to record at a distance, will be the result. Continents shall be crossed. This great and wide sea shall be no barrier…. As he sat upon the deck [of the ship] after the conversation at dinner, he drew from his pocket one of [his sketch books], and began to make marks to represent letters and figures to be produced by the agency of electricity at a distance from the place of action.[9]

The successful implementation of Morse's concepts for a "system of signs" correlated to patterns of "electricity made visible" with the agency of electromagnetic circuits marks the beginning of global electronic telecommunications (the "Victorian Internet" in Standage's apt phrase).[10] Morse's code concept, which was further developed by his co-inventor, Alfred Vail, was the first abstraction method for encoding the values of typographic signs in a system of physically structured, electrical pulses used as a semiotic substrate. The final system, adapted for International Morse Code, was a proto-binary system of long and short pulses with pauses or spaces. [Diagram and illustration] Morse's original design concept included a receiving relay for transferring and boosting the current for electromagnetic motions that could *automatically record* the pulses as strings of imprinted code (typically on tape), a process he considered his crowning achievement—the *tele-graph*. Telegraphic coders, however, whether using wired or wireless systems, soon preferred to decode more quickly by transcribing the audible pulses in a sounding device.[11]

Although there were several almost simultaneously invented electromagnetic telegraph designs in the early 19th century, Morse's dot, dash, space system transmitted through networks of relays and switches became universally adopted, and his model became paradigmatic and implemented in many brands of equipment.[12] Morse also explicitly describes the semiotic motivation for creating a symbolic abstraction method assigned to units of electrical signals.[13] We're still in the long tail of Morse's telegraph. Everything from telegraphic ticker tape systems, forms of electromechanical teletype in the 20th century, and, more recently, logic switches implemented in transistors, byte code standards for ASCII and Unicode characters, and the entire structure of binary electronics are direct descendants of Morse's proof of concept.

In this foundational moment for electronic communications, we can reinterpret Morse's discovery in Peirce's terms: using electricity as the agency of sign actions, the units of electricity "made visible in any desired part of [the] circuit" could be organized in rule-governed patterns for re-tokening the sign values of typographic symbols in a physical substrate, a substrate both materially and temporally *different from* the message units themselves, whether written on paper or spoken orally for encoding. By abstracting sign *types* (the set of alphanumeric characters and symbols) from specific material *token instances*, Morse discovered a way to decompose and recompose signs by translation into electro-magnetic structures for *interpretable sign units*. The Morse implementation is the first extensible method for using patterns of electronic signal switches as *indexical signs for symbolic tokens*, by causing electro-magnetic *actions* in telegraphic devices wired to send, receive, and register the patterns of switched current; that is, a design for instantiating sign *types* by de- and re-composable physical electronic structures mappable to *n-instances* (tokens) of typographic symbols, which, by concatenation, represent the token strings of the interpretable message units that motivated the transmission.

I would like to point out some of Peirce's revealing comments about telephones, telegraphs switches, and logic machines as a context for reconsidering his semiotic philosophy for modern computing systems.

Peirce was born in Cambridge the same year that Morse met Louis Daguerre in Paris (1839). Morse brought the method of Daguerre's photography back to New York and set up a famous studio there. Peirce's father, Benjamin Peirce, was a leading mathematician and scientist and well-connected to Brahmin society.[14] Peirce was no armchair academic semiotician. His semiotic philosophy developed from several decades of work in science, mathematics, logic, and the history of philosophy, and began his scientific career at the Harvard Observatory and in the US Coastal and Geodetic Survey, of which his father was director. He lived through, experienced, and participated in the scientific and technical advances of his own era (electricity, telegraph, telephone, logic machines, and early computing machines). By the time Peirce was a student at Harvard, an international telecommunications network was already in place (he sent and received telegraph messages often), and telephones were beginning to take over the telecom network that was already in place. He attended, with his father and the intelligentsia of Boston, Alexander Graham Bell's famous demonstration of the telephone -- "voice over telegraph" -- in Boston in 1877. Peirce's first job was as a "computor," that is, someone skilled in making exact mathematical calculations for logarithm tables and other kinds of scientific measurement. His father was head of a committee that bought and brought a Scheutz difference engine, a successor design after Babbage, to the observatory in Albany to aid in astronomy calculations.

After around 1903, Peirce redefined his project of “logic as semeiotic” to include sign systems in all kinds of material or technical mediations. In 1904, he stated: “ideas cannot be communicated at all except through their physical effects. Our photographs, telephones, and wireless telegraphs, as well as the sum total of all the work that steam engines have ever done, are, in sober common sense and literal truth, the outcome of the general ideas that are expressed in the first book of the *Novum Organum* (MS 774, 1904, “Ideas, Stray or Stolen;” EP 2.327). (Peirce is referring to the treatment of inductive logic and scientific method in Francis Bacon’s famous work.) Earlier in this paper, Peirce states:

> [The term] "sign" [includes] every picture, diagram, natural cry, pointing finger, wink, knot in one's handkerchief, memory, dream, fancy, concept, indication, token, symptom, letter, numeral, word, sentence, chapter, book, library, and in short whatever, be it in the physical universe, be it in the world of thought, that, whether embodying an idea of any kind (and permit us throughout to use this term to cover purposes and feelings), or being connected with some existing object, or referring to future events through a general rule, causes something else, its interpreting sign, to be determined to a corresponding relation to the same idea, existing thing, or law…. (MS 774, 1904, “Ideas, Stray or Stolen;” EP 2.326.)

In 1909, Peirce stated that semeiotic “considers Signs in general, a class which includes pictures, symptoms, words, sentences, books, libraries, signals, orders of command, microscopes, legislative representatives, musical concertos, performances of these" (MS 634:17-18, 1909). Similarly, in 1907: “*Sign* will here be the general name for everything of that sort [used for representation], whether it be an instrument of music, a mental resolve, a voyage of discovery, or anything else that plays an essential part in the spread of intelligence” (MS 602, 1907, pp.7-8).[15] A Peircean orientation to symbolic technologies from telephones to computers would thus reveal these as fundamentally *semiotic artefacts* designed for and motivated by “the spread of intelligence,” the same nineteenth-century term for communication that Morse used for his telegraph system.

In a manuscript from 1904 that has not yet been discussed, Peirce describes physical sign actions and the interpretability of signs in the technical system of telephone signals:

> Every thought, or cognitive representation, is of the nature of a sign. "Representation" and "sign" are synonyms. The whole purpose of a sign is that it shall be interpreted in another sign; and its whole purport lies in the special character which it imparts to that interpretation. When a sign determines an interpretation of itself in another sign, it produces an effect external to itself, a physical effect, though the sign producing the effect may itself be not an existent object but merely a type. It produces this effect, not in this or that metaphysical sense, but in an indisputable sense….
> Consequently, the whole purport of any sign lies in the intended character of its external action or influence. Some signs are interpreted or reproduced by a physical force or something analogous to such a force, simply by causing an event; as sounds spoken into a telephone effect variations or the rate of alternation of an electric current along the wire, as a first interpretation, and these variations again produce new sound-vibrations by reinterpretation. Another case is where a sign excites a certain quality of feeling, simple or complex, which quality of feeling is a sign of anything that partakes of it, as the sound of the word "red" may make us imagine the color red. (MS 1476, 1904, pp. 5-6; p.4, second sequence of drafts.)

There are several drafts of this argument in the manuscript; in another, probably earlier, draft Peirce words it this way:

> Some signs are interpreted in actual physical effects or in relations analogous to such effects; as when sound vibrations of speech before a telephone transmitter cause variations in the rate of alternation of an alternating current along the wire, this series of variations making up a sign that interprets, i.e. translates, the acoustic sign, and in its turn setting up new acoustic vibrations in the receiver, as a reinterpretation. (MS 1476, 1904, p. 5, sixth sequence of drafts)

In this fascinating text, Peirce describes how the design for using electrical energy states generated within the technical system itself are assigned semiosic actions directed toward physical interpretability (reproduction of voice sounds). In a letter to Victory Welby in 1909, Peirce explains his kinds of interpretants: "My Immediate Interpretant is implied in the fact that each Sign must have its peculiar Interpretability before it gets any Interpreter. My Dynamical Interpretant is that which is experienced in each act of Interpretation and is different in each from that of any other; and the Final Interpretant is the one Interpretative result to which every Interpreter is destined to come if the Sign is sufficiently considered. The

Immediate Interpretant is an abstraction, consisting in a Possibility" (Welby Correspondence, March 14-15, 1909; SS 108-119). This seems to be the way he would frame the teleological semiosis in the electrical transmission of interpretable signals, the very structure which contemporary electronic digital computing exploits at any scale.

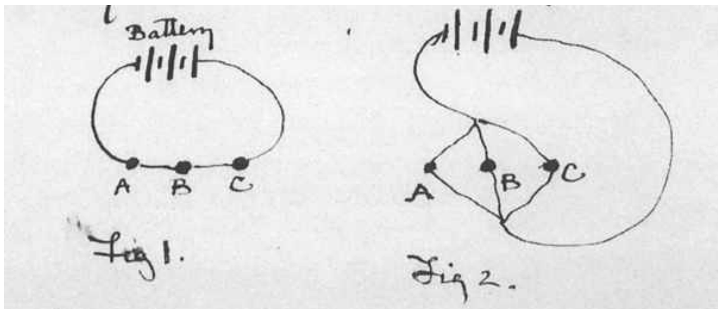
Peirce and Logic Machines

Around 30 years after Morse's first implementation of a system of signs in electrical circuits, C. S. Peirce began considering the possibilities of logic or reasoning machines as ways of physically implementing the necessary patterns of symbolic logic. Peirce knew the design of the Jacquard loom with pattern-automating punch cards, the history of calculating machines and Charles Babbage's work, and he was the leading American logician-mathematician who promoted George Boole's work for symbolic logic. There were many logic and calculating machines known by the 1870s, and speculation about what these machines could do was beginning in the philosophical community long before Turing.[16]

In my current research in progress on Pierce's comments on machines from 1871 to 1912, I've found 160 references to logic machines and computing engines in both published texts and unpublished papers. But Peirce's interest in semiotic artefacts extends much further. He frequently discusses many kinds of instruments and devices as embodiments of semiotic processes: hydrometers, wind-speed measuring devices, thermometers, pendulums for gravitational calculations, cameras and photographs, maps, clock hands and alarm clocks, telescopes and photographs of telescope images, and ink and writing materials as forms of externalized symbolic cognition. I can't develop this discussion further here, but Peirce finds that anything formally necessary in mathematics and logic can be automated in, and delegated to, a corresponding machine process designed to render some kind of interpretable state. Peirce thus began a foundational investigation into what we now call the hypotheses of extended mind, cognitive artefacts, distributed cognition, and distributed agency in cognitive science.[17]

After publishing his ground-breaking papers that extended Boole's algebra to a fuller logic of relations, Peirce wrote a paper on "Logical Machines" in 1887, which expanded on ideas that he taught in his courses in logic at Johns Hopkins University. One of his students, Allan Marquand, designed a working mechanical logic machine. In 1886, Peirce wrote a letter to encourage his student to improve his design by using electrical rather than mechanical action. To illustrate, Peirce drew the first diagram of electronic logic switches, elementary Boolean logic gates that correspond to modern NOR and NAND gates used in all computing circuits. Peirce states:

I think you ought to return to the problem [of the design for the logic machine], especially as it is by no means hopeless to expect to make a machine for really very difficult mathematical problems. But you would have to proceed step by step. I think electricity would be the best thing to rely on.



Let A, B, C be three keys or other points where the circuit may be open or closed. As in Fig 1, there is a circuit only if all are closed; in Fig. 2. there is a circuit if any one is closed. This is like multiplication & addition in Logic. (Letter to Allan Marquand, 1886, W 5.421-22)[18]

Peirce proposes using electromagnetic circuits like those used in telegraphy for Boolean logic gates that map symbolic logic onto the states of the circuit (open/closed). Peirce combined the technologies of the telegraph, logic machines, and Babbage's engines redesigned with an electrical mapping of Boolean algebra for what could have been used for an *electronic* analytical engine. Allan Marquand did work out an electrical switch design for his logic machine (though not implemented),[19] [diagrams] and we can wonder why Peirce didn't continue this development further. Peirce's papers are scattered with notations and calculations in binary mathematics, and he even developed a binary cypher code for encrypting telegraphic signs around 1902.[20] [Image of MS page]

Peirce considered all machines to be logic machines since they implemented abstract concepts and regularized natural forces through mathematical engineering principles. Peirce wrote in 1906:

There certainly is something marvellously beautiful in Boole's algebra. Only it is not that. It is something that the mind untrained in logic perceives but cannot distinctly analyze. Falling into this natural mistake, it is supposed that the great problem in inventing an algebra or other system of logical representation is to create something equivalent to a calculating engine. The untrained mind does not see that every machine

> whatever is a logical machine working out incessantly new conclusions from premisses as long as the steam is kept up. (MS 498, 1906, p. 883)

In his many references to logic and reasoning machines, Peirce is clear that automation is possible if machine signs could be assigned logical self-control, that is, rational, intentional regulation:

> it is quite true that we cannot make a machine that will reason as the human mind reasons until we can make a logical machine (logical machines, of course, exist) which shall not only be automatic, which is a comparatively small matter, but which shall be endowed with a genuine power of self-control; and we have as little hopes of doing that as we have of endowing a machine made of inorganic materials with life. Indeed, it shall be shown in a future article that these two attributes, growth and *self-control*, are confronted with closely analogous difficulties, and further that if we could endow a system of signs with self-control, there is very strong reason to believe that we should thereby have conferred upon it a consciousness… (MS 283, 1906, "The Basis of Pragmaticism," EP 2.387)

Unfortunately, Peirce's work on Boolean electric logic gates was unknown after the 1880s, and the same method proposed by Peirce was re-invented by Claude Shannon in 1936-38 and independently by Conrad Zuse in the mid-1930s.[21] Adopting Boole's values 0 and 1 to represent open and closed switched circuits, Shannon remarked in his MIT master's thesis that "it is evident that a perfect analogy exists between the calculus for switching circuits and this branch of symbolic logic. Due to this analogy any theorem of the calculus of propositions is also a true theorem if interpreted in terms of relay circuits."[22]

[Shannon diagram]

Shannon's rediscovery and application of Boolean logic to telephone circuits – Morse 2.0 -- is the most consequential development for all of modern communications and computing. The important point is that Peirce not only glimpsed the possibility of *automating* logical operations formally represented in Boolean symbols in electrical circuit designs but he also understood how symbolic representations and actions could be decomposed into chains of indexical actions and physical interpretants assigned to electrical states which then return recomposed interpretable symbolic structures in a perceptible substrate (significant sounds or visual transcripts). The models for automated, or *automatable*, semiosis begin here.

On Peirce's Philosophy of Signs and Symbolic Processes

Over the past 15 years, there has been an explosion of interest in Peirce's work across many sciences and disciplines, and I couldn't hope to summarize it here. Peirce's triadic models of sign functions and progression of interpretant processes in semiosis are also well-known, and I won't rehearse the foundational assumptions here.[23] Rather, I'd like to propose a new synthetic model of sign processes based on his later writings and unpublished comments on reasoning machines. This is an interdisciplinary work in progress for developing a new heuristics for a detailed semiotic description of computing architectures, digital information and media, and the design of our main semiotic interface, the graphical user interface (GUI) in pixel grid screens and displays.

All diagrams of semiosis fail unless they capture durations and sequences in time, but this is a snapshot view of the stacks of processes that Peirce describes in various ways in his mature writings:

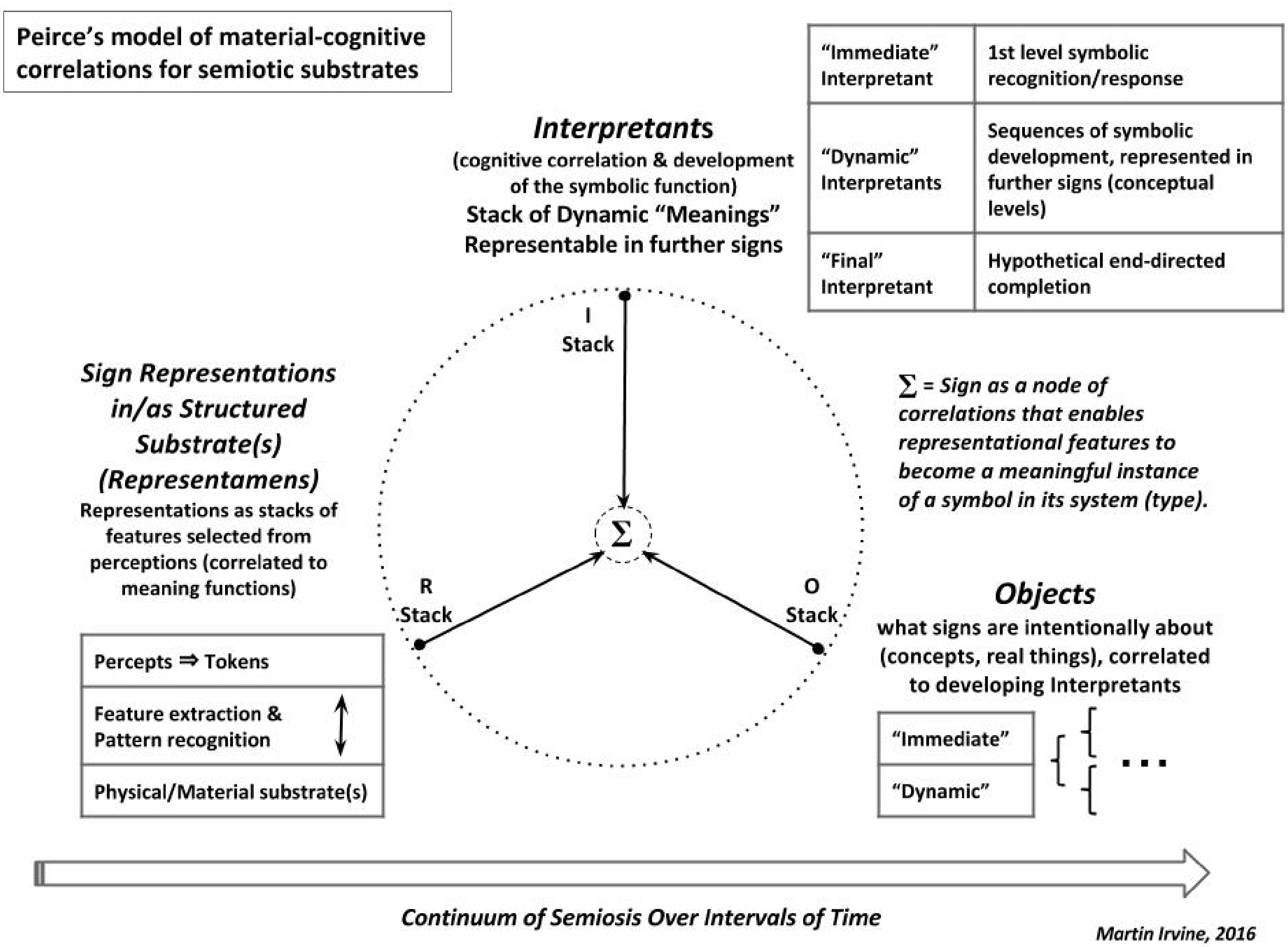


Figure 1
Sign/semiosis: From percepts and reactions to sign-mediations

Peirce continually emphasized that his “division” of signs (a labyrinth of distinctions that expands recursively on itself) was a logical abstraction, and not a description of discrete, isolatable sign types. As Peirce discussed many times, all our ordinary symbolic representations from writing and photographs to algebra function as *composites* of indexical, iconic, and general symbolic sign functions, depending on the sign systems being used and within a pragmatic situation. A photograph in any substrate can be simultaneously interpreted as indexical evidence, iconic resemblance, or a cultural symbol correlated to complex cultural meanings in unlimited chains and networks of interpretants.

Symbolic activity moves across modes and functions, layers and levels, including compounding in stacks or “strata” as he termed it in 1902:

> In consequence of every sign determining an Interpretant, which is itself a sign, we have sign overlying sign. The consequence of this, in its turn, is that a sign may, in its immediate exterior, be of one of the three classes, but may at once determine a sign of another class. But this in its turn determines a sign whose character has to be considered. This subject has to be carefully considered, and order brought into the relations of the strata of signs, if I may call them so, before what follows can be made clear (MS 425a, CP 2.94).

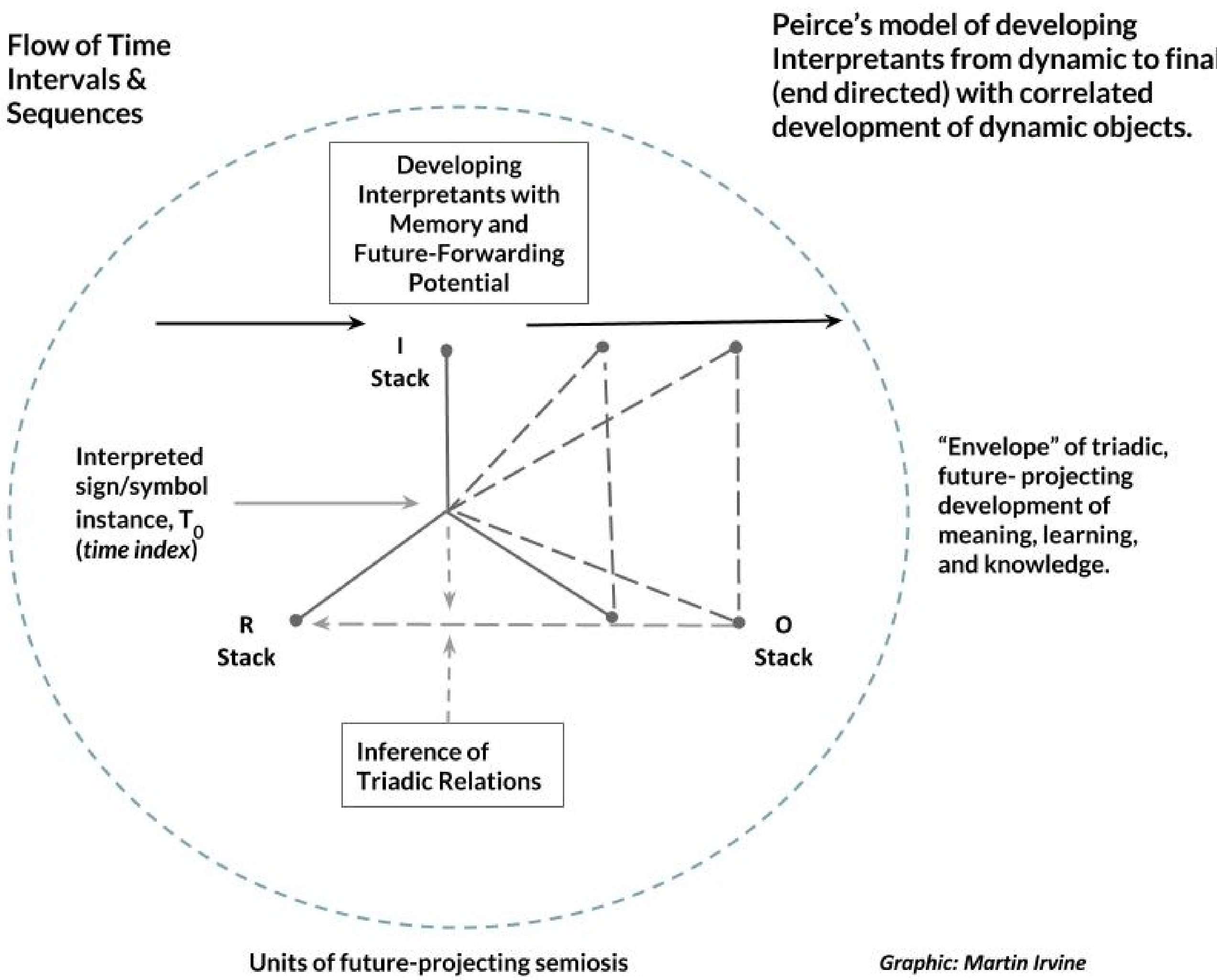


Figure 2
A Model of Peirce's Semiosis Extensible to Computing

As a processual model, meaning generation is explained, not by introspection or psychological states, but by interpretable trails in signs and their uses. From around 1906-1910, Peirce refocuses his model of sign functions around mediation and he reemphasizes his anti-psychologistic framework for symbolic cognition that included *quasi-minds*. Peirce's quasi-mind is close to our contemporary notion of cognitive agent, how any semio-cognitive agency would act in performing semiosic mediation—supplying the Third correlate. For Peirce, quasi-minds include non-human agents like bees and delegated sign action in reasoning machines:

> [A] Sign may be defined as a Medium for the communication of a Form. It is not logically necessary that any thing possessing consciousness, that

> is, feeling or the peculiar common quality of all our feeling should be concerned. But it is necessary that there should be two, if not three, *quasi-minds*, meaning things capable of varied determinations as to forms of the kind communicated.
>
> As a *medium* the Sign is essentially in a triadic relation, to its Object which determines it, and to its Interpretant which it determines….
>
> That which is communicated from the Object through the Sign to the Interpretant is a Form; that is to say, it is nothing like an existent, but is a power, is the fact that something would happen under certain conditions. (MS 793, 1906, pp.1-3)

In this period, Peirce frequently elaborates on the sign as medium and how sign effects can be described as determinations on quasi-minds.[24] This description is really one or two steps away from describing a programming language and designs for allocating memory for operations on sign units.

Classes (and Sub-classes) of Signs Based on Kinds of Correlations: Icon, Index, Symbol

Within this overall framework for thinking about semiotic technologies, I want to outline ways to use Peirce's concepts for describing our contemporary computing architectures.

The functions of what Peirce termed icons, indices, and symbols for sign functions and sign actions correspond exactly to the designs for contemporary computing devices with graphical user interfaces indexed to internal system-implemented software processes. This would not surprise Peirce in the least: he often stated that any machine designed to automate logical processes would succeed if properly implemented. And we have a further step in technical intermediation. Contemporary GUI interfaces – in concept, design, and physical implementation -- provide both 2D representations of media objects and a Janus-like bi-directionality for mediating and translating agency to unlimited levels of motivated background sign translations in the 3D physical computing architecture as a substrate for configurations of token structures and operations on them.

What we colloquially call a graphical icon is, in Peirce's terms, a software-generated pixel array representing a composite symbol and icon with an index assigned to it. A GUI icon is designed to translate human agency begun as an interpretant response into symbolic actions by splitting into cascading sequences of indices to, from, and in computational processes in the physical substrates of a computing device. GUI designs combine sign functions with sign agency at multiple interface levels: between and among cognitive agents (users/interpreters individually and distributed in groups) using software in common, and between individual cognitive agents and the whole computational substrate for representing signs and symbols and receiving actions for operations.[25]

Peirce correctly observed that the physical-perceptible ground of any kind of sign or symbol is revealed in the capability and necessity of repetition—iteration, replication, re-presentation in any material medium providing affordances for physical realization or instantiation. The repetition in iterable patterns is also a function of the bi-directionality of token to type mappings, either in interpretation or realizations in new expressions. Considering how we begin interpreting signs through a representamen (whatever functions as an interpretable form):

> The mode of being of a representamen is such that it is capable of repetition. … It is the same with a diagram or picture. It is the same with a physical sign or symptom. If two weathercocks are different signs, it is only in so far as they refer to different parts of the air. A representamen which should have a unique embodiment, incapable of repetition, would not be a representamen, but a part of the very fact represented. This repetitory character of the representamen involves as a consequence that it is essential to a representamen that it should contribute to the determination of another representamen distinct from itself. (MS 312, 1903, Fifth Harvard Lecture, EP 2.203)

Indices

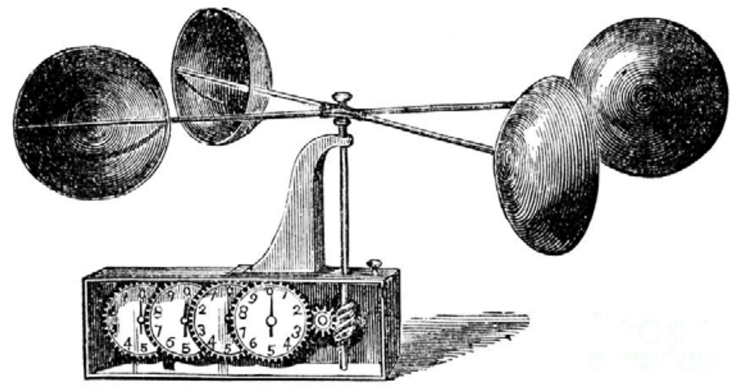
Peirce expanded the concept of the index, or indexical function, throughout the last decade of his life. He described many kinds and subclasses signs used with an indexical function: (1) deictic signs (pointing and indicating through gestures for joint and focused attention; linguistic indicators in context like calling out "hey" or "over there;" personal pronouns that reference or indicate antecedents).[26] (2) Causally connected correlated indications, either in humanly designed instruments or as inferences drawn from regularities in nature (thermometer gauge → read as temperature in a scale of values; smoke → fire; row of bricks stood on end communicating a "domino effect" action, falling brick → prior brick). (3) Abstract and conceptual signs used in mathematics (the conventional letters used to label the angles of a triangle, letters and notational symbols used in any formal system). (4) Maps, which are designed to have indexical, iconic, and symbolic functions.

Peirce also included expressions in the imperative mood as examples of indexical sign agency: "Imperative signs have the person addressed & his conduct as their field of interpretation. The action sought to be produced is the Interpretant." (MS 339, 1905, f. 254r). The meaning of expressions like "do *x*," (e.g., "stop," "close the window," "please be seated"), which normally assume one or more addressees, is taken as a signal for a kind of action; that is, we translate the sign tokens through the semantic-symbolic gateway into *indexicals* for actions beyond a semantic value (EP 2.288, 1906). In interactive computing, imperative sign structures underlie all interface components down though many linked software layers. "Do" is a universal software program imperative function with many forms.

Indexical sign uses require an interpretive correlation, interpretants, which are usually handed off to symbolic interpretation. A representation on a thermometer or car speedometer can't mean anything (cannot be interpretable) without a semiotic agent, Peirce's quasi-mind, supplying learned rules of correspondence which involve symbolic values correlated to the representations for states or conditions indexed.

In an unpublished draft of a dictionary definition on "Exact Logic," Peirce describes how instruments combine indices, icons, and symbols:

> It is true, however, and highly important in the development of exact logic, that the different kinds of symbols are connected in certain ways. An index points to its object in certain respects, and it must refer to some icon of those respects. A Robinson's anemometer is a purely physical representamen, or index, of the wind. It may be arranged to record upon a chronograph the instant at which every ten miles of air has passed by it. The chronograph record is thus made the interpretant of the anemometer, in a purely physical way. Now, the intervals between the records on the chronograph-fillet constitute an icon of the behaviour of the wind. A little reflection will enable the reader to convince himself inductively that an icon is thus connected with every index. In like manner, a symbol cannot existentially denote anything, without appealing to an index to represent the individual denoted. (MS 1147, 1901, draft numbered pp. 10-11; MS is a folder of pages in no continuous order.)



(Figure, Robinson Anemometer)

In Peirce's logical scheme for classes of signs in 1903-04, he explained how some indexicals have cross-mappings to other sign functions. Indices can be reflexive, "An *Index* can very well represent itself. Thus, every number has a double; and thus the entire collection of even numbers is an Index of the entire collection of numbers, and so this collection of even numbers contains an Index of itself. But it is impossible for an Index to be its own Interpretant" (MS 478, 1903, EP 2.276). What Peirce termed a "Dicent Sinsign," a single information-announcing sign, affords information of an actual fact (like weather vanes and all measuring instruments), by using both iconic and indexical functions (resemblances and interpretable correlations of value) (MS 540, 1903, EP 2.294; MS 800, p.2, 1903).

Peirce also described the agency of signs and sign actions. "The agency of the sign" results from the perceptible-cognitive correlations that generate Interpretants as actions, mental and physical, and further developed responses from enacted behavior.[27] "[W]e may take a sign in so broad a sense that the interpretant of it is not a thought, but an action or experience…" (1904, Welby Letter, CP 8.332). Recall Peirce's description of interpretants in the variations of current in telephone voice signals. Peirce held that self-controlled thought and reasoning – logic and mathematics – are *actions* with and in sign users, and he also understood sign agency as parallel and isomorphic actions delegated to logic machines and any device designed to register physical states.

> [It is] characteristic that signs specially [i.e., ordinarily] function between two minds, the one being the sign's *utterer* (not necessarily a

> vocal utterer, but putting forth the sign in any way), the other the sign's *interpreter*. Indeed, a mind may, with advantage, be roughly defined as *a sign-creatory in connection with a reaction-machine*. (MS 318, 1907, from version f., sheets 18-22, MS sequence 425-434, p. 18, seq. 425)

"Creatory" is here used with analogy to repository, and refers to how any "quasi-mind" develops meanings from sensory information by adding Interpretants.

Computer science has a rich repertoire of "index"-like terms and metaphors, such as index registers, addresses, indexed variables, pointers, calls, lookups, directories, file names, and many other related concepts. "Index" is a common term used in databases, allocations of memory (hardware), and references to logical data "positions" in programming and database code (software). In Web search engine schemes, an index is the complete table of Web addresses that can be pointed to in search results. A URL or Web address is an index to a file location on Internet-connected server (real or virtual).

Peirce explains the future conditional of interpretants when a semiotic agent is situated to develop higher-order general concepts from compound structures or sequences of indices and icons representable in further sign patterns.

> The being of a symbol consists in the real fact that something surely will be experienced if certain conditions be satisfied. Namely, it will influence the thought and conduct of its interpreter. Every word is a symbol. Every sentence is a symbol. Every book is a symbol. Every Representamen depending upon conventions is a symbol. Just as a photograph is an index having an icon incorporated into it, that is, excited in the mind by its force, so a symbol may have an icon or an index incorporated into it, that is, the active law that it is may require its interpretation to involve the calling up of an image, or a composite photograph of many images of past experiences, as ordinary common nouns and verbs do… (MS 492, c. 1903, "Logical Tracts, 2, 'On Existential Graphs, Euler's Diagrams, and Logical Algebra'.")[28]

Representations, Indexicals, Replicas, and Tokens: Re-tokenization

Semiotic agents are inference engines for associating sign token features with multiple levels of abstraction in sign types. Peirce's distinction between *type* and *token* is now commonly adopted in various ways in philosophy, linguistics, and computer science. Tokens are the material-perceptible *instances* of signs and symbols, and, as such, exist in unlimited repetition, iteration, replication, or reproduction. As Peirce summarizes in 1906:

> By a Type, I mean a general form which can be repeated indefinitely and is in all its repetitions one and the same sign. Thus the word *the* is a Type. It is likely to occur over a *score* of times on a page of an English book; but it is only one word twenty times repeated. The distinction between a Type and a Token is obvious. (MS 399, 1906, f. 276r [dated in Peirce's hand "1906 April 2"])

Photographic prints or unlimited digital "copies" are tokens of an ideal, even lost, image-type. The sign or symbol *type mappings* (which do the cognitive work) are cognizable through the structured *percepts* derived from the material features of sign representations in medium-specific instantiations.

Considering tokenization and indexing in computing substrates, the replicable patterns of binary electronic states allow us to split and redistribute signs in *n*-instances of *de-* and *re-tokenization* across computing and memory substrates in space and time. Re-tokenization and substrate re-distribution is a function of the independence of type levels from material-instance levels in symbolic representations and artefacts. Re-instantiation over structured material substrates is what unifies the use of indices, icons, and symbols as intersubjective, collective cognitive, and agency translators. At no time do the symbolic processes exit material, physical states: digital representations and computational processes are equally physical at all levels.

Computation as Automatable Semiosis: Semiosic Substrates and Distributing the Sign

Combining Peirce's insights on material sign substrates, the role of indices in technical mediation, the tokenization of types, and structure of symbol representations and operations, we have a rich descriptive and conceptual base for understanding computation and digitization as semiotic processes.[29] Many dimensions of computing logic, software design, and physical system architecture can be usefully described and explained with a Peircean semiotic model, but I will focus here on a top-level description of the implemented principles that are directly visible to ordinary users at the interface level of contemporary interactive graphical systems.

As background, we should have brief description of the "symbol + operations" architecture. Modern electronic digital computers of any size or scale are designs for correlating *symbols representing meanings or values + symbols for operations (actions) on other symbols* in such a way that the physical system architecture can *combine symbols for meanings and symbols for operations* in automated sequences over intervals in time. The semiosic processes of operations is marked by *symbols representing logically necessary relations* among and between other symbols that determine outcomes.[30] The semiotic leap in electronic digital design is found in directing the correlations between ways to *represent* the necessary rule-governed transitions of logic and mathematics (the building blocks of algorithms) and embody them in completely regular and consistent time-stepped transitions in the discrete architecture of a computing system. The whole physical architecture is predicated on one macro design concept: using symbols-to-operations correlations for generating interpretations on symbols-as-information. This is more precise way of describing what we call the distinction between *data* (or "content" representations) and *code* (software).

To make executable code from the texts of our high-level programing languages (in, say, Java or Python today), we write interpretant programs, compilers, translate the written text of a program into binary machine code (executable, "runnable" code physically indexable to memory locations). Compilers are metaprograms, sequences of abstract interpretants designed to direct the semiosic process for mapping one set of symbolic representations into others that can *physically enact* the rules-to-actions transitions in a physical machine. As Peirce noted, the interpretants of one class of signs can be in another class of signs.

Likewise, an algorithm is a model of an *interpretant machine*, an abstract symbolic representation of these two kinds or levels of code and encoding. An algorithm is an abstract structure of relation-making and necessary entailment requiring sequences of time, state transitions, to transform input representations into output representations. Algorithms are metasymbolic at high orders of abstraction, and they must be designed to do what's computational possible in finite time. Since these abstract models represent patterns of necessary transitions, they can be automated.

Pushing Pixels: The Pixel Grid Substrate

All contemporary GUI designs are *semiotic interfaces*; that is, designs for using the affordances and constraints of the physical substrates (pixel-grid screens correlated to structures in computing architecture) for projecting interpretable software-output representations, combined with the conventions for indicating the two-way mapped locations (links, icons, menus, dialogue boxes, buttons, etc.) used as the channels for communicating agency to software processes.[31] Our standardized interactive GUI computing and digital media interfaces are designed for, presuppose as addressees, semiotic agents who enact symbolic interpretations over the pixel arrays of screen representations and direct agency through defined physical locations in a two-dimensional *pixel grid*. The development of GUI screens and standard for all digital media have enabled us to design a meta summation of all prior 2D sign systems, a substrate for the history of representational substrates.

The orchestrated complexity of abstraction layers in contemporary graphical systems sum up into pushing interpretable pixel arrays out to user-interpreters who motivate the semiosic loops and cycles of interactive computing that output displayable/playable digital media artefacts with their many symbolic dimensions. The visible tokens appearing in our physical screen substrates are composed of *observable* and *unobservable* material display layers, *unobservable* electrical current that powers the pixels, and many equally *unobservable* layers of software for maintaining indexed memory locations and pixel coordinates in the architecture of the computing device.

Today's standard interactive GUI pixel grid is designed as a Janus-face bi-directional interpretant, displaying software outputs of interpretable representations and for communicating human agency and intentions to other software interpretants that mediate agency to many levels of the physical architecture.[32] The pixel grid in any device screen is thus not only an interface in the ordinary user-facing GUI sense; it is an indexical interface to the whole computing system designed to produce outputs as projections into screen pixel arrays for interpretable *token instances* of sign types and complex combinations of all representable symbol structures. Software and systems design return interpretable symbolic clusters for which one kind of interpretive response is an action with the interface for both inserting new representations (texts, images, etc.) and directing actions into the cycle of background computations in the software layers that chain indices and abstract icons for internal interpretants and returning further symbolic representations.

A grid is a well-known mathematical object of a type Peirce frequently explained: a grid represents a finite section of the infinite 2-dimensional plane mapped out in x/y axes with specified scales of units. We can make an iconic sign of the abstract mathematical relations in a graph (points or locations on an x/y axis, like lines on a sheet of graph paper), but the abstract iconic pattern is useless without corresponding indices to physical locations that produce arrays of symbolic patterns. A pixel grid is translated from an abstract icon into indexical signs with potential symbolic value precisely when activated as an assignment of physical indices in a screen material substrate (like the standard 1920 x 1080 pixel dimensions for an HD screen, image, or video frame). A pixel is yet another extrapolation of Morse's "electricity made visible in any desired part of a circuit" with assigned values. A computer screen, and any defined section of it (e.g., a "window" displaying a photo, a chunk of text, or video frame) are pixel arrays representing a few million measurements of the colors and intensity of visible light assigned to coordinate locations in the x/y axis. (A virtual z axis can be added to the grid for simulating 3D effects, objects, shadow effects, and window layers.) A specific device screen with its aspect ratio of pixels is designed as a *tokenization* of a mathematical grid linked to the physical architecture of graphics controllers and memory combined with the software interpretant layers that project and manage the final assignments of specific coordinate locations for rendering the interpretable pixel arrays.

As Alan Kay and early designers of screen interfaces discovered, the computer screen with underlying software controls could become a *metamedium*, a medium or substrate for representing and interactively transforming other media.[33] The GUI platform design could only have developed at the moment of digital convergence, when graphical software could be designed to create a summation and integration of the whole history of human sign systems (translated to their digital types) on 2D substrates, especially those using the affordances of paper. The early designers of the GUI interface features at Engelbart's lab and Xerox PARC were focused on the engineering problem of simulating the representational features of paper as a 2D substrate in the raster display. The main designer of the influential GUI interactive system, the Xerox Alto, states: "Only one technique is known for approximating all these properties of paper in a computer-generated medium: a raster display in which the value of each picture element is independently stored as an element in a two-dimensional array called a bitmap or frame buffer."[34] The term "bitmap" refers to the design technique of "mapping" the visible pixel array to a chunk of contiguous memory (in bytes). The bitmap-to-pixel array is thus a two-way index, depending on what view of the system you are taking (the visible screen or the memory cells assigned by software).

The whole system design -- from the level of representations interpreted by users as cognitive agents to the unobservable symbolic processes instantiated in the physical substrates of a computing device -- is a model of multidimensional semiosis in distributed and delegated processes with physical substrates: sign processes, sign agency, and sign tokens in materialized instances enacted through multiple interpretant pathways correlated to types of symbolic relations through physical intervals in time. Interactive computing exemplifies Peirce's notion that interpretants are always in the future, projections of past and present configurations by signs mediating into a *potential future* when conditions are such that sign agency can be completed in an interpretant response. As we say, it's semiosis all the way down.

The GUI interactive semiotic leap was discovering that since software can control both side of the bitmap, any coordinates of the x/y locations of the pixel grid can be configured with recognizable indexical, iconic, and symbolic functions, and also defined in interpretable contexts as interactive "channels" for communicating user intentions for ongoing software processes (links, icons, or any pixel region designed for pushing pixels).[35] Identical designs for actions are also directed touch screens: the "presence of electricity made visible in any part of a circuit" is now reengineered to be correlated to human touch, movements, and gestures. The human body itself is the source of voltage changes in the electrical capacitance layers overlaying the pixel coordinates. Our fingers modify the electrical charges running across a grid indexed to the pixels that are in turn indexed to symbols-that-mean and symbols-that-do.

In our current system architecture with pixel-based screen, all screen representations are interpreted, rendered, as graphical information regardless of the data types and background processes that have created their outputs. I find it conceptually useful to consider the arrays of pixels activated in our screen substrates as patterns projected from the system's graphics processor. A type "font" is a digital file in memory with encoded definitions for correlating abstract character code values (typically Unicode vales) to stylized pixel arrays interpreted through the graphics processor from other software layers. In semiotic terms, a computer "font" is a set of iconic *types* (the abstract, platform-independent definitions) designed to be interpretable for assignment to memory indices and translation, in any software context, to pixel token instances. Our interpretation of displayed token instances of pixel patterns enacts the standard semiotic *feature extraction to pattern recognition* process for inferring regularities and continuities as *types*. We find many internal indexical structures and software interpretants for pattern correlations rendered as token instances of the characters in the indexed typographic "font" style. (It's revealing that both Apple and Google are recently reinforcing the 2D paper and materials metaphors in standards for app interface designs.)

In short, we can *split* signs: re-tokenize across substrates, decompose features, distribute tokens as objects filling variables in software process, and recompose units in their combined indexical, iconic, and symbolic functions in display interfaces. Peirce frequently discussed derived and reduced signs (using the term "degenerate" from geometry). Signs can be derived from, split off from, complex symbolic structures to form simpler signs like the operations in geometry for representing 2D planes as intersections or slices of 3D objects; that is, decomposing a sign structure into simpler constituent elements open for recomposition in an interpretation in another form. For example, it's easy to trace a line drawing from a photograph, by hand or in software, and form a simpler contour drawing minus the photographic information. (Andy Warhol's many screen print images derived from photographs are just such a technique, prompting multiple interpretant paths when viewed as paintings, prints, and photo-derived images.) A line drawing or monochrome print is not a photograph, but it can preserve interpretable (and re-composable) structures by feature selection.

Indexical signs can be decomposed (lose a present mental correlation) into motivated signals and still function as signs by interpretive recomposition. In computation and digital media, we split and transcode signs as structure-preserving morphisms, in Joseph Goguen's category-theoretic terms, translations that preserve the features of symbolic potential for recomposition in other defined interpretive contexts.[36]

This splitting of sign indexical components from more complete sign structures yields "a representamen which represents a single object because it is *factually* connected with it, but which conveys no information whatever" (1903, EP 2:171–172) (i.e., no information in the Peircean, not Shannon, sense). Peirce's terms usefully describe how we can map binary patterns, units of abstract types of mathematical values, "factually" onto electronic states in actual physical architectures; that is, we can explain semiotically how and why mathematical values can be correlated to patterns of physical voltage states that are in turn interpretable as units of symbolic value when supplied sign-constructing interpretants. Physical states in themselves are *not* signs, but can *represent* them by instantiating indexed patterns in a computing substrate (memory locations and transition states in processing), patterns which are held as recomposable in pixel representations of symbolic, interpretable units. This intra-indexical structure is required and implemented millions of times in any software process at multiple meta and physical component levels (like registers and operating system controlled assignment of memory space and dedicated memory in graphics microprocessor chips). The specific computing product implementations that we use are based on multiple combinatorial layers of sign functions and the ability to use indexical functions for producing actions in a system through a cascade of linked software processes which return recomposed symbolic representations.

Digital user interfaces to the internal computational symbolic states are thus designed to correlate *meanings*, *actions, and material structures*. Computation and correlated interfaces allow us to enact the dual functions of semiosis by specifying symbols that *mean* things and assigning actions to symbols that *do* things, in which the combined process, over any number of iterations, is designed to return potentially unlimited chains of further interpretable symbolic representations.

Programming, software, and digital media object representations are based on recursively chaining indexical and iconic signs split off from composite sign structures (e.g., letter forms, graphic elements, sections of a digital photograph) into structure-preserving states that can be recomposed and completed as unified symbolic structures by human cognizers supplying interpretants for recognizable representations. Human symbolic cognition always holds half the program, as it were, and motivates both the design architecture *for*, and creation of, individual token instances in and across the physical substrates. In all programming and digitization methods, these electronic, material sign components in binary representations follow end-directed logic for "returning values" as interpretant outputs in the symbolic representations projected into the grid locations of our interpretable pixel arrays. (Again, combining symbols that mean and symbols that do, signs for cognitive-abstractive-conceptual *meanings* and signs for *actions*).

By extending Peirce's descriptions of the material-conceptual correlates in symbolic activity, we have a more complete set of concepts for productive explanations of computation and digitization as designs for mediated symbolic action through *motivated sign distributions in re-presentable instances across multiple material substrates* in 2, 3 and 4 dimensions. Since both individual sign units and complex symbolic structures (e.g., connected discourse, musical forms, images, film) are decomposable and recomposable at multiple levels of constituent forms, we are able to produce an unlimited series of *retokenizations* (new instances of symbolic types or sets/classes of types in other material forms) across instantiations in different material substrates in time and place, the whole architecture of networked and distributed computing.

Conclusion

We're at one momentary summation of a cumulative continuum in semiotic technologies and technical mediation as artefacts of human symbolic cognition. We have a long cultural history of 2D material substrates as a primary "user interface" for symbolic mediations, remediations, and sign token redistributions from clay and wax tablets to computer tablets, from the codex book (through script and industrial print production transitions) and all kinds of writing supports to ebooks and "pages" on screens, from painting, drawing, and image supports of all kinds to projections and displays on 2D screens. While material semiotics reminds us that all material media are culturally encoded prior to the registration of specific symbolic "content," the long history of retokenizations and redistribution of sign functions across, in, and through material substrates is an incontrovertible fact. Software and digitization enables automation of semiosic processes and unlimited retokenization in the design of computer systems for *structuring and processing transformations of symbolic states.*

The systematic redescription of computing systems and digital media representations and processes is not merely an academic or philosophical project. My 20 years of teaching topics in technology, media, communication, and semiotics convinces me that we need a new integration of knowledge that unites the "human sciences" with all knowledge domains. By expanding on a "Peircean paradigm" heuristically, we have an opportunity to unify approaches to the cultural, technical, mathematical, and scientific bases of symbolic thought for reappropiating computation, software, and digital media in the context of human interests.

The deeper origins of computing emerged from a synthesis of thought and human interests that knew no boundaries or partitions in knowledge domains, whether cultural, philosophical, mathematical, or scientific. "Machine" is only a metaphor for automation, not a reduction to instrumental mechanization. Computation and code for automated semiosis use *general technologies* instrumentally in actual computers for implementing sign processes, but computation as a modelling system for embodying semiotic actions and symbolic media representations is a *symbolic-cognitive artefact*, not a machine product.

By repositioning symbolic mediation and the computational automation of symbolic actions in this longer continuum of cumulative cultural, cognitive, material, and social implementations, we have a far more productive way to embrace and incorporate computational knowledge in research, theory, and practical expertise in all disciplines. Further, this repositioning enables non-technical people to reclaim ownership over our cognitive symbolic technologies, not as alienating machine products controlled by specialists or as determinist instruments of our recent political economy, but as implementations of core human cognitive-symbolic capacities in live social-material situations.

We can reposition the intellectual and technical history of the ideas that motivated the designs for computing and technical mediation in the longer continuum that begins with humanists like Morse and polymaths like Peirce. A different trajectory, a longer continuum in the code base, emerges. Computation and digital media are artefacts of human symbolic cognition implemented in physical substrates designed to use "electricity visible in desired parts of circuit" as energy for instantiating and enacting patterns of automatable semiosis. In short, we *own* this, in every sense of the term. Computation and the open possibilities for information representation and interpretation are co-extensive with our core human operating system, collective symbolic cognition. Computation is a human design for complex, multileveled *automated semiosis,* distributed through digital material substrates and their structured time-state transitions, motivated by returning values for human interpretation. Computation and digital media processes are designed as structures of symbols that *mean* things inter-specified with symbols that *do* things in the most sophisticated way we've yet invented.

> And in every age, it can only be the philosophy of that age, such as it may be, which can animate the special sciences to any work that shall really carry forward the human mind to some new and valuable truth. Because the valuable truth is not the detached one, but the one that goes toward enlarging the system of what is already known.

C. S. Peirce, MS 442, 1898, “The First Rule of Logic,” CP 5.583.

The valuable truth is recovering the position of computation and digital media that has been hiding in plain sight in the longer continuum. Recovering this tradition of thought provides a new foundation for unifying humanistic, scientific, and technical concerns. All computing, being fundamentally semiosis-dependent, is, finally, *humanistic computing*.

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Notes

[1] I presented an earlier version of this paper at *The Digital Subject: Codes* conference, University of Paris 8, November, 2015. I am grateful for discussions with colleagues at this conference, which helped me improve the argument and motivated further research.

[2] I will develop this conception in a book-length project, which will involve a synthesis of research in complex systems theory, linguistics, cognitive science, semiotics and sign systems research, theory of computation and information, and HCI and design theory.

[3] Many of Peirce's concepts for describing meaning and information processes are being productively reinterpreted in many contemporary research communities. For framing my approach, I'm indebted to the work of many colleagues working at an interdisciplinary nexus of interests in semiotics, cognitive science, linguistics, and computing: Anderson, Goguen, Sowa, Denning, Gomes, Gudwin, El-Hani, and Queiroz in computing and cognitive science; Skagestad, Tanaka-Ishii, Nöth, and Nadin (in philosophy, logic, and computational semiotics); and Kockelman and Enfield (in linguistic anthropology).

[4] As early as 1873, Peirce noted: "A sign is an object which stands for another to some mind. I propose to describe the characters of a sign. In the first place like any other thing it must have qualities which belong to it whether it be regarded as a sign or not. Thus a printed word is black, has a certain number of letters and those letters have certain shapes. Such characters of a sign I call its material quality" (W 3.66). A sign "must have characters which shall enable us to distinguish it from other objects" (W 3.82). In 1897, the features are what enables sign/symbol instances to known as such: "A sign, or representamen, is something which stands to somebody for something in some respect or capacity. It addresses somebody, that is, creates in the mind of that person an equivalent sign or perhaps a more developed sign. That sign which it creates I call the interpretant of the first sign" (CP 2.228).

[5] Dyson, *Turing's Cathedral*, Preface, ix.

[6] Peirce's work is continually being rediscovered for insights in other fields, and valuable ground-work has been done in applications of Peirce's semiotics and algebra of relations in theories of computation, knowledge representation, cognitive artefacts, and HCI and digital media.

Representative works include: Andersen, *A Theory of Computer Semiotics*; Andersen, “A Semiotic Approach to Programming”; Brier, *Cybersemiotics*; de Souza, “Semiotic Approaches to User Interface Design”; Nadin, “Information and Semiotic Processes: The Semiotics of Computation”; Goguen, “An Introduction to Algebraic Semiotics, with Application to User Interface Design”; Goguen and Harrell, “Information Visualization and Semiotic Morphisms”; Gomes, Gudwin, and Queiroz, “On a Computational Model of the Peircean Semiosis”; Gomes, Gudwin, and Queiroz, “Towards Meaning Processes in Computers from Peircean Semiotics”; Kockelman and Bernstein, “Semiotic Technologies, Temporal Reckoning, and the Portability of Meaning. Or”; Meystel, “Intelligent Systems”; Nadin, “Semiotic Machine”; Nöth, “Semiotic Machines”; Nöth, “Representation in Semiotics and in Computer Science”; Queiroz, Emmeche, and El-Hani, “A Peircean Approach to ‘Information’ and Its Relationship with Bateson’s and Jablonka’s Ideas”; Ransdell, “The Relevance of Peircean Semiotic to Computational Intelligence Augmentation”; Skagestad, “Thinking with Machines”; Skagestad, “The Mind’s Machines”; Sowa, *Knowledge Representation*; Sowa, *Conceptual Structures*; Sowa, “Future Directions for Semantic Systems”; Tanaka-Ishii, *Semiotics of Programming*.

[7] For background, see: Brownlee, *Samuel F. B. Morse’s “Gallery of the Louvre” and the Art of Invention*; Silverman, *Lightning Man*; Morse, *Samuel F.B. Morse*; Prime, *The Life of Samuel F. B. Morse, LL. D.*

[8] Prime, *The Life of Samuel F. B. Morse, LL. D.*, 137.

[9] Ibid., 253.

[10] Standage, *The Victorian Internet*.

[11] For primary historical background: Morse, *Samuel F.B. Morse*; Library of Congress, “Samuel F. B. Morse Papers at the Library of Congress, 1793-1919 | Collections | Library of Congress”; Prime, *The Life of Samuel F. B. Morse, LL. D.*; Mabee, *The American Leonardo*; Silverman, *Lightning Man*; Hochfelder, *The Telegraph in America, 1832-1920*.

[12] For background, see: Beauchamp, *History of Telegraphy*; Huurdeman, *The Worldwide History of Telecommunications*; Hochfelder, *The Telegraph in America, 1832-1920*; Sterling and Shiers, *History of Telecommunications Technology*; Standage, *The Victorian Internet*.

[13] The accounts of the various designs for telegraphic devices in the prior note reveal that other inventors simply take a corresponding encoded signal system for granted or focus on engineering and marketing motives. Other inventors do not discuss the ideas motivating Morse’s broader sense of code and representational media.

[14] See Brent, *Charles Sanders Peirce (Enlarged Edition), Revised and Enlarged Edition* and the introductions to both volumes of the Essential Peirce.

[15] Further summing up his philosophical orientation in a letter to the English philosopher of language, Lady Victoria Welby (1837–1912), Peirce writes: "[I]t has never been in my power to study anything, – mathematics, ethics, metaphysics, gravitation, thermodynamics, optics, chemistry, comparative anatomy, astronomy, psychology, phonetics, economics, the history of science, whist, men and women, wine, metrology, except as a study of semiotic." (1908, SS: 85–6).

[16] For historical background on Peirce and computing, see Ketner and Stewart, "The Early History of Computer Design"; Burks, "Review"; Burks, "Peirce and the Year of the Computer"; Ketner, "Peirce and Turing"; Burks and Burks, *The First Electronic Computer*, 333–54.

[17] Brandt, "Toward a Cognitive Semiotics"; Daddesio, *On Minds and Symbols*; Dror and Harnad, *Cognition Distributed*; Perlovsky, "Symbols: Integrated Cognition and Language"; Rieger, "Semiotic Cognitive Information Processing: Learning to Understand Discourse, A Systemic Model of Meaning Constitution"; Sowa, "Cognitive Architectures For Conceptual Structures"; Terenzi, "Semiosis in Cognitive Systems"; Zlatev, "Cognitive Semiotics."

[18] References to Peirce's works are in the conventional citation format for the published editions (see Bibliography).

[19] See Gardner, *Logic Machines and Diagrams*, 104–13; Burks and Burks, *The First Electronic Computer*, 340–47; Buck and Hunka, "W. Stanley Jevons, Allan Marquand, and the Origins of Digital Computing"; Marquand, "A Machine for Producing Syllogistic Variations."

[20] There are many relevant texts still in manuscripts of Peirce's unpublished papers: For example, MS 1361 (c.1902): telegraph cypher code in binary strings, and MS 425a (1902), "Reasoning by Machinery."

[21] See Shannon, "A Symbolic Analysis of Relay and Switching Circuits," December 1938; Zuse, *The Computer - My Life*.

[22] Shannon, "A Symbolic Analysis of Relay and Switching Circuits," December 1938, 174. This is the published version of his thesis which was written in 1936, submitted in 1937, and approved for his degree in 1940. Vannevar Bush was one of his thesis directors. See: Shannon, "A Symbolic Analysis of Relay and Switching Circuits," 1940.

[23] For essential background, see Liszka, *A General Introduction to the Semiotic of Charles Sanders Peirce*; Short, *Peirce's Theory of Signs*; Misak, *The Cambridge Companion to Peirce*.

[24] See MS 283, "The Basis of Pragmaticism," ed. in part, EP 2.371-97; MS 339, The Logic Notebooks: "A sign is a species of medium of communication. The object, O, determines the sign, S, and S determines the Interpretant sign, I, to being determined by O through S." (Jan. 30, 1906, f.271r.)

[25] Many studies over the past 20 years confirm this description from different theoretical perspectives: see Nadin, Goguen, Sowa, de Souza, O'Neill, Cantwell-Smith.

[26] For a good overview of research on this class of symbolic actions, see McNeill, *Language and Gesture*; West, *Deictic Imaginings*. The Latin etymology of the word *index* (mark, sign, pointer, indication) also includes the *index finger*, and thus reveals the deep association of pointing and indicating in embodied signs for spatial-temporal attention markers in a parallel modality with spoken and visual representations used indexically.

[27] MS 634, 1909, "Essays on Meaning, Preface," p. 22.

[28] This is a long MS with variant drafts. The quoted passage corresponds to selections from the MS published in CP 4.447.

[29] Recent studies that apply Peircean semiotics to computing architectures include: Tanaka-Ishii, *Semiotics of Programming*; Skagestad, "The Mind's Machines"; Rocchi, "How Semiotics Can Improve Our Knowledge on Computing"; Rocchi, *Logic of Analog and Digital Machines*; Rocchi, "What Is Information."

[30] See the excellent history of operations in Priestley, *A Science of Operations*.

[31] Many of the major expositions of HCI and GUI design principles are implicitly, if not explicitly, based on managing semiotic structures and actions; see Kazmierczak, "Design as Meaning Making"; Moggridge, *Designing Interactions*; Norman, "Cognitive Artifacts"; Dourish, *Where the Action Is*; Suchman, *Human-Machine Reconfigurations*; Goguen, "An Introduction to Algebraic Semiotics, with Application to User Interface Design"; Nadin, "Information and Semiotic Processes: The Semiotics of Computation."

[32] See Agre and Rosenschein, *Computational Theories of Interaction and Agency*; Goldin, Smolka, and Wegner, *Interactive Computation*; de Souza, *The Semiotic Engineering of Human-Computer Interaction*; Wegner, "Why Interaction Is More Powerful Than Algorithms"; Nadin, "One Cannot Not Interact."

[33] Kay and Goldberg, "Personal Dynamic Media"; See Kay, "The Dynabook - Past, Present, and Future"; the continuing relevance of Kay's metamedia concepts are explored in Manovich, *Software Takes Command*.

[34] Thacker et al., "Alto: A Personal Computer," 556.

[35] For an accessible overview, see: Tanimoto, *An Interdisciplinary Introduction to Image Processing*.

[36] At the data level, this is operationalized in dozens of transcoding schemes for preserving the interpretability of material structures while changing their total characteristics (compression, format conversion, and device or client properties).

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