Small Thinking

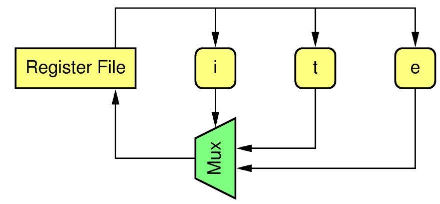
Although people often think of the primary contributions of computer technology as being PCs, the Internet, or supercomputing for "grand challenge" problems, by far the most direct impact of computer technology on society has been the ability to make a wide range of ordinary devices "intelligent." Programmable control is everywhere – except in devices that are too small to fit a microcontroller. The NANOCONTROLLERS we propose require orders of magnitude less circuitry, enabling nanocontrollers to fit alongside or under the devices they control in applications like:

- Imaging sensors used in digital cameras lose image quality due to applying the same gain and integration time settings to all pixels. With a nanocontroller per pixel, each pixel can be adjusted independently and calibrated corrections for defects applied, yielding much greater dynamic range and lower noise.
- Chemical and/or biological sensor array chips use small electrical changes in carbon nanotubes to detect and measure the levels of a wide range of chemical and biological toxins; a million-sensor chip would naturally output a million weak analog signals to be decoded elsewhere. Placing a nanocontroller *under each sensor* not only allows calibrated correction of sensor defects in software, but also would allow data to be directly output as digital PPM concentrations of the toxins sensed – or even as digitized audio messages saying what protective gear is needed.

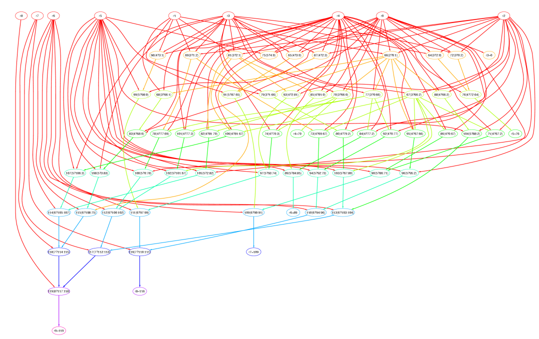
Not all nanocontroller applications are controlling physically small devices; for example, large programmable sheets of printed organic semiconductor materials offer equally impressive possibilities. To enable these and other applications, nanocontrollers must have the following properties:

- **Minimal Circuit Size**: no more than a few hundred transistors per nanocontroller
- **Predictable Real-Time Behavior**: computations must meet real-time control constraints
- **Localized Input/Output**: each nanocontroller must talk with the device it controls
- **Coordination As A Parallel Computer**: nanocontrollers must work together to reduce external I/O to an acceptable level (e.g., summarizing sensed values rather than passing them all off-chip)
- **Each Nanocontroller Independently Programmable**: nanofabricated devices often have significant manufacturing variations that require individualized correction, perhaps even different algorithms
- **Reprogrammability**: it must be possible (but not necessarily fast) to reprogram a part to correct for defects that develop over time or to enhance functionality

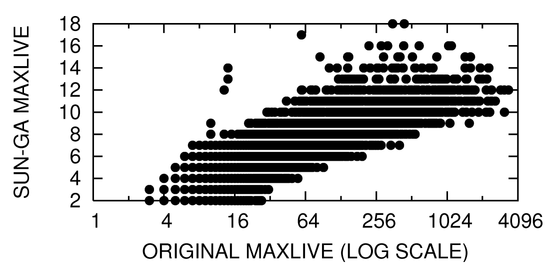
The key to this is actually a compiler technology that allows millions of independent programs to be merged into a single state machine while preserving relevant timing properties. This technology, called META-STATE CONVERSION, makes independent program memories unnecessary – *nanocontroller circuit complexity is not proportional to program complexity.* In combination with aggressive use of new compile-time optimization technologies (from gate-level logic optimization to a new genetic algorithm for code ordering and register allocation) and a very simple 1-bit datapath, digital nanocontrollers require at most a few hundred transistors; switched-analog nanocontrollers might be feasible using just a few dozen transistors. A digital nanocontroller consists of tens of 1-bit registers and a 1-of-2 input multiplexor:



Even simple computations require many 1-bit multiplexor operations. For example, squaring an 8-bit integer yields the DAG:



These DAGs often have MAXLIVE orders of magnitude larger than the number of registers available. We have solved this problem by developing a genetic algorithm (SUN-GA) that can restructure the code to drastically reduce MAXLIVE at the expense of performing a modest amount of redundant computation, with the amazing results summarized below:



At this writing, all the key nanocontroller technologies have been demonstrated except for the placement of logic *under* nanofabricated sensors. We are now working on prototyping nanocontrolled imaging sensors and welcome collaborators for various applications.

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