Neuro-inspired Computing Systems & Applications

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Outline

• Technology Transformation
• Neuron Modeling
• Neuro-inspired Systems/Chips
• Concluding Remarks
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Massive amounts of data is generated.

A new style of IT emerging

Every 60 seconds

- 98,000+ tweets
- 695,000 status updates
- 11 million instant messages
- 698,445 Google searches
- 168 million+ emails sent
- 1,820TB of data created
- 217 new mobile web users

Source: https://practicalanalytics.files.wordpress.com/2012/10/newstyleofit.jpg
Technology Transformation

Constant Increase of the number of transistors/cores

Data collected by M. Horowitz, F. Laborie, O. Shacham, K. Olukotun, L. Hammond, C. Batten
There are many emerging technologies.
RAF (Reliability Acceleration Factor), which represent the efficiency of the applied fault-tolerances, is given by the following equation:

$$\text{RAF} = \frac{\lambda_{\text{original}}}{\lambda_{FT}} = \frac{\text{MTTF}_{FT}}{\text{MTTF}_{\text{original}}} \geq 1$$ (1)

Where:

- $\lambda$ is the fault rate and it is the inverse value of Mean Time to Failure ($\text{MTTF}$).
- $\text{MTTF}_{\text{original}}$ is the MTTF of the original system.
- $\text{MTTF}_{FT}$ is the MTTF of the fault-tolerant system.
Technology Transformation
Robust Scalable NoC

<table>
<thead>
<tr>
<th>Model</th>
<th>Area ($\mu m^2$)</th>
<th>Power (mW)</th>
<th>Speed (Mhz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static</td>
<td>Dynamic</td>
<td>Total</td>
</tr>
<tr>
<td>Baseline router [2]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Router</td>
<td>29,780</td>
<td>10.017</td>
<td>2.2574</td>
</tr>
<tr>
<td>Serialization</td>
<td>3,318</td>
<td>0.9877</td>
<td>0.2807</td>
</tr>
<tr>
<td>TSV Sharing</td>
<td>5,740</td>
<td>0.7863</td>
<td>0.2892</td>
</tr>
<tr>
<td>Total</td>
<td>38,838</td>
<td>11.7910</td>
<td>2.8273</td>
</tr>
</tbody>
</table>

Single layer layout illustrating the TSV sharing areas (red boxes). The layout size is $865\mu m \times 865\mu m$.

The sharing TSV area are the red boxes. Each sharing area has 8 clusters for 4 ports and 2 routers.

Technology Transformation
Robust Scalable NoC
Technology Transformation

Hybrid Electro-Photonic NoC

3D-PHENIC System Architecture
Technology Transformation

What is the issue with the current computing technology?
What is the issue with the current computing technology?

Scalability issue.
What does that mean?
Technology Transformation

What does that mean?

i. Transistor nbr doubles every year, but we cannot get energy to operate the whole chip - Dark Silicon.

ii. We double the number of transistors with smaller sizes, but we are producing much more heat in the same space.

iii. The speed of the chip increases, but the memory bandwidth does not keep-up.
John von Neumann Machine

stored-program Computer.
John von Neumann Machine

stored-program Computer.

“Computers are like humans- they do everything except think.”
John von Neumann
Neuro-inspired Computing

Why is the brain computing style better?
Neuro-inspired Computing

Why is the brain computing style better?

BECAUSE

✓ Consumes low power - ~20W)
✓ Fault tolerant - brain continues to operate even when the circuit (neuron, neuroglia) is died)
✓ Works in parallel - >10^6 parallelism vs. <10^4 for VN)
✓ Faster than current computers - i.e. simulation of a 5 s brain activity takes ~500 s on state-of-the-art supercomputer [US PTN 20160125287A1]
✓ Learn and think - needless to prove 😊
Neuro-inspired Computing

How do we design this new brain-like machine?
How do we design this new brain-like machine?

WE NEED

- **New Software**
  - Parallel programming abstraction

- **New Hardware**
  - Massively Parallel
  - Scalable connectivity
  - Low-powered cores
Type of Neuro-inspired Computing Systems

- **Neuromorphic Sensors** - electronic models of retinas and cochleas.
- **Smart sensors** — tracking chips, motion, pressor, auditory classifications and localization sensors.
- **Models of specific systems**: e.g. lamprey spinal cord for swimming, electric fish lateral line.
- **Pattern generators** — for locomotion or rhythmic behavior
- **Large-scale multi-core/chip systems** — for investigating models of neuronal computation and synaptic plasticity.

March 1, 2018
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There are three known level of connections in the Human Cortex:

- connectivity of local microcircuit
- within-area connectivity with space constant
- long-range connections between areas
Neuron Modelling

Biology: Single Neuron

Machine Learning

Weights

Transfer function

Activation function

Neuron

Dendrites

Suma

Axon

Neuron
Neuron Modelling

Biology: Tree Neurons

Machine Learning

convolution

fully connected

March 1, 2018
How neurons communicate?

1. An electrical signal travels down the axon.
2. Chemical neurotransmitter molecules are released.
3. The neurotransmitter molecules bind to receptor sites.
4. The signal is picked up by the second neuron and is either passed along or halted.
5. The signal is also picked up by the first neuron, causing reuptake, the process by which the cell that released the neurotransmitter takes back some of the remaining molecules.
• Computing with precisely timed spikes is more powerful than with “rates”. [W. Maass, 1999]
Electronic device vs chemical device

- Deliver the concentration difference of $K^+ , Na^+$
- Action potential $\sim 80$ mV
  - Extreme low voltage operation
  - Noise problem
  - Multiple signal input/ integration

- Spatial and temporal multiplexing $\rightarrow$ Active sharing of the interconnect
- Chemical computing, extremely low operation voltage ($<100mV$) $\rightarrow$ Low power
Fundamental interactions

« Integrate and fire » model: spikes are produced when the membrane potential exceeds a threshold.
Action Potential (Synapse) Storage

(Dr. Leon Chua, 1971)

The electrical resistor is not constant but depends on the history of current that had previously flowed through the device.

- Voltage **pulses** can be applied to a **memristor** to change its **resistance**, just as **spikes** can be applied to a **synapse** to change its **weight**.
Wiring via AER (Asynchronous)

Courtesy: iStock/Henrik5000)
Spike-timing-dependent plasticity (STDP)

- Adjusts the strength of connections between neurons in the brain.
  - Adjusts the connection strengths based on the relative timing of a particular neuron's output and input action potentials.
NASH: Neuro-inspired Architectures in Hardware

Integration & Fire

Membrane potential

Reset

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NASH: Neuro-inspired Architectures in Hardware

inputs

outputs

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LIF Neuro-core for NASH System

Diagram:
- Xi(t) – Spike input to the synapse
- Si – synaptic weight
- Vj(t) – Membrane potential
- αj – Neuron threshold
- Λj – Leak value

Table 1: Area Evaluation

<table>
<thead>
<tr>
<th>Item</th>
<th>NC-1N</th>
<th>NC-4N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Internal Power</td>
<td>6.9680 μW</td>
<td>20.5040 μW</td>
</tr>
<tr>
<td>Net Switching Power</td>
<td>4.8271 μW</td>
<td>14.8272 μW</td>
</tr>
<tr>
<td>Total Dynamic Power</td>
<td>11.7950 μW</td>
<td>35.3312 μW</td>
</tr>
<tr>
<td>Cell Leakage Power</td>
<td>4.6943 μW</td>
<td>14.3147 μW</td>
</tr>
</tbody>
</table>

Table 1: Power Evaluation

<table>
<thead>
<tr>
<th>Item</th>
<th>NC-1N</th>
<th>NC-4N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combinational Area</td>
<td>186.998 μm</td>
<td>562.856001 μm</td>
</tr>
<tr>
<td>Non-Comb Area</td>
<td>47.88002 μm</td>
<td>213.864000 μm</td>
</tr>
<tr>
<td>Total Cell Area</td>
<td>234.878002 μm</td>
<td>776.720001 μm</td>
</tr>
</tbody>
</table>

Placement of LIF-1N (Left) and LIF-4N (right)

Application I

Neuro-inspired Hardware System for Image Recognition

Application II

Neuro-inspired Hardware System for Autonomous Vehicles

Application III

Neuro-inspired Hardware System for Visual Pattern Recognition in FARM Monitoring

Fig 4. System overview: OASIS FMS-1

Fig 3. CNN example

Out: Rich feature hierarchies for accurate object

Fig 6. Learning result

Best test accuracy: 92.647

- pig
- other

Application IV
Brain-inspired Drone Control with BCI

Flight navigation logic (in C++/Python)
- Emotiv community SDK
- Parrot ARDrone SDK
- Other libraries
  - Facial command
  - Mental command
  - Raw EEG
  - Gyro
- Drone control
- Video inputs
- Sensor inputs
- Spiking neurons
- Neural networks
- SLAM (mapping)

Brain to Brain drone system

Numerical computation with SNNs

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Conclusion & References


Thank you!

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