December 11th, 2025
Session 2

Pushing the Limit:

Embedded Intelligence and the Physics of SWaP in Future SIGINT Systems

AOC 2025 International Symposium & Convention

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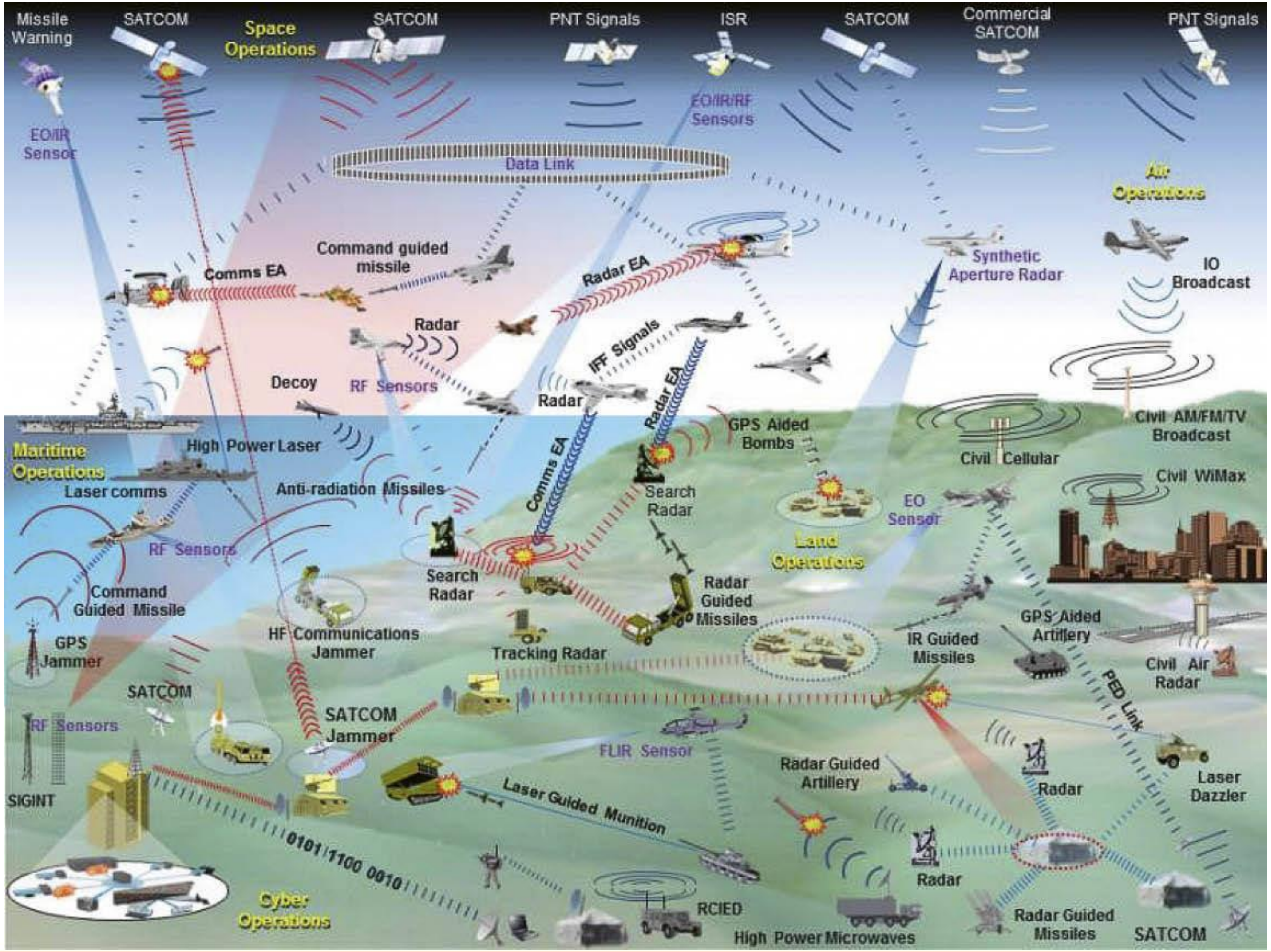
What are we going to talk about?

- Evolution of SIGINT in EW
- SWaP: “What we want” vs “What we can have”
- Why the AI Assumption is Dangerous
- Embedded Intelligence over AI
- Thermodynamics and Electromagnetics
- Light Speed : Photonics and Fiber
- Neuromorphic Architecture
- Distributed Sensing and Decentralized Intelligence
- Thermal-Aware Materials
- Now, what do we do?

Evolution of SIGINT in EW



Demands

- Greater adaptability
- Faster performance
- Smaller packaging
- More accuracy
- Less power

Issues

- EMP E1 (fast pulse)
- GMD/E3 (slow pulse)
- Cascading Impacts
- Hardening

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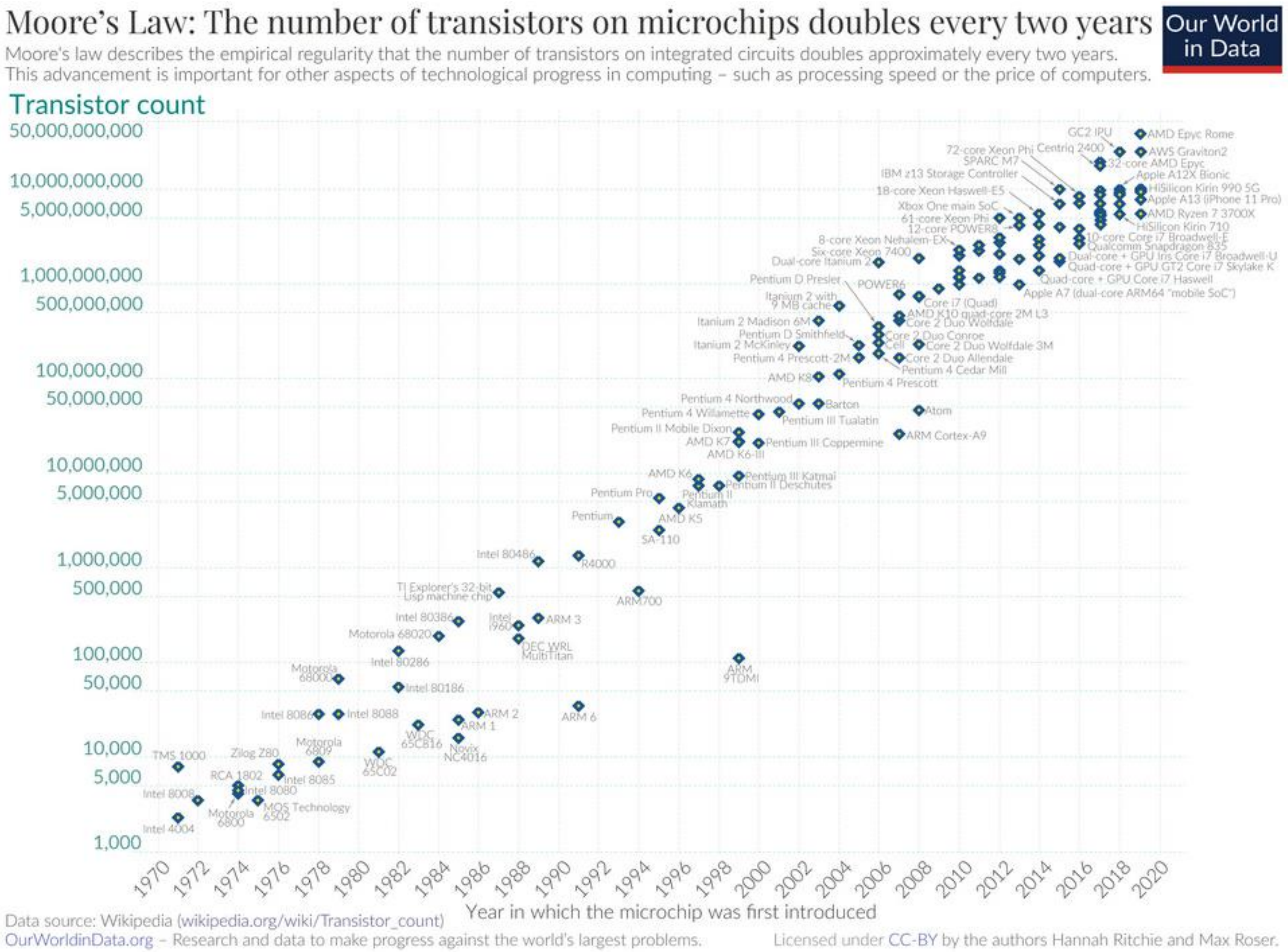
SWaP: “What we want” vs “What we can have”



- **Bekenstein boundary** — the maximum information that can be stored or processed within a given mass-energy budget
- **For every watt spent on computation, another half watt goes into thermal management**
- Power Usage Effectiveness Ratio — hovers around 1.3 - **One third of all AI energy is cooling**.
- We are talking about **adaptive** AI

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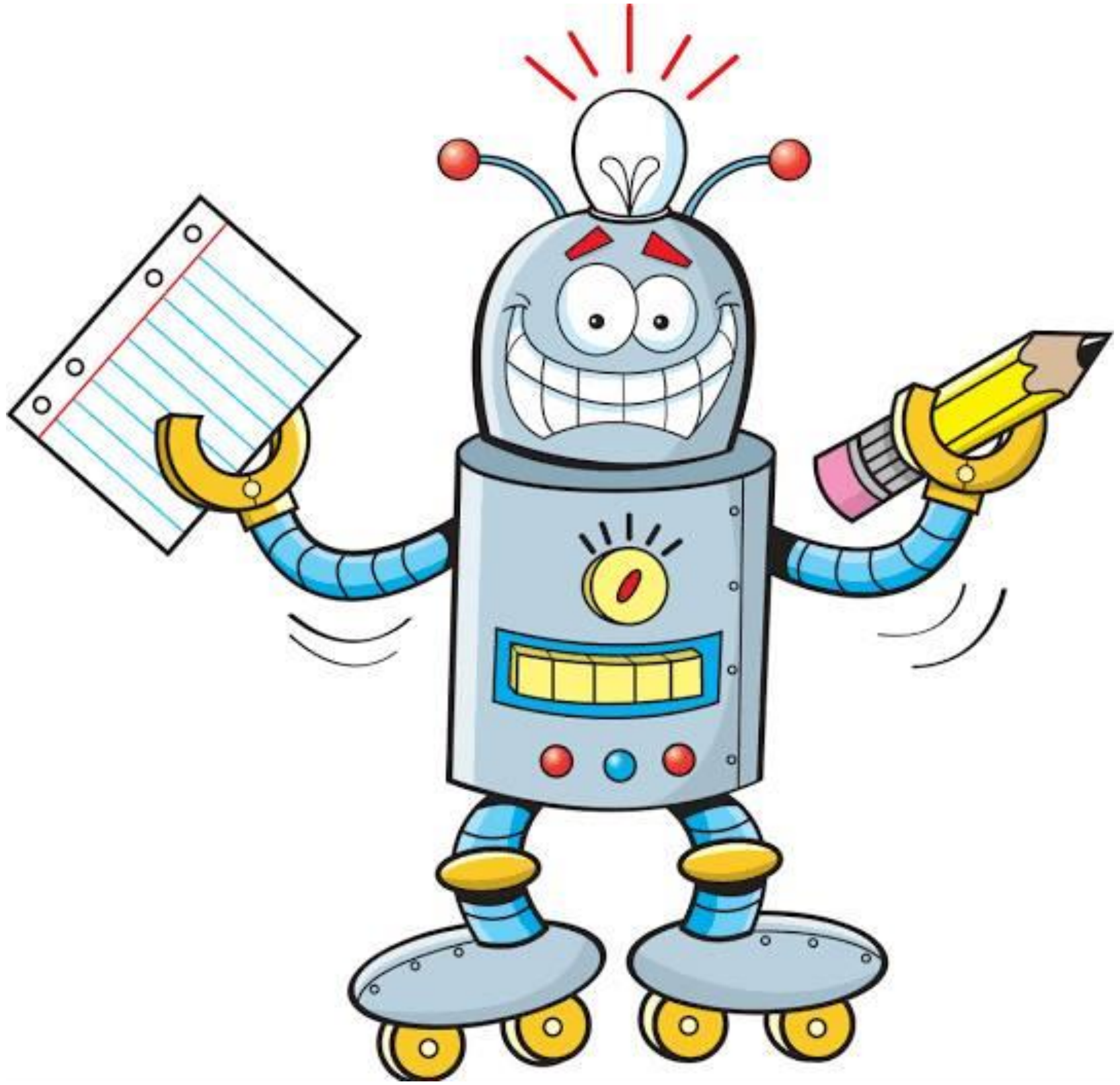
Why the AI Assumption is Dangerous

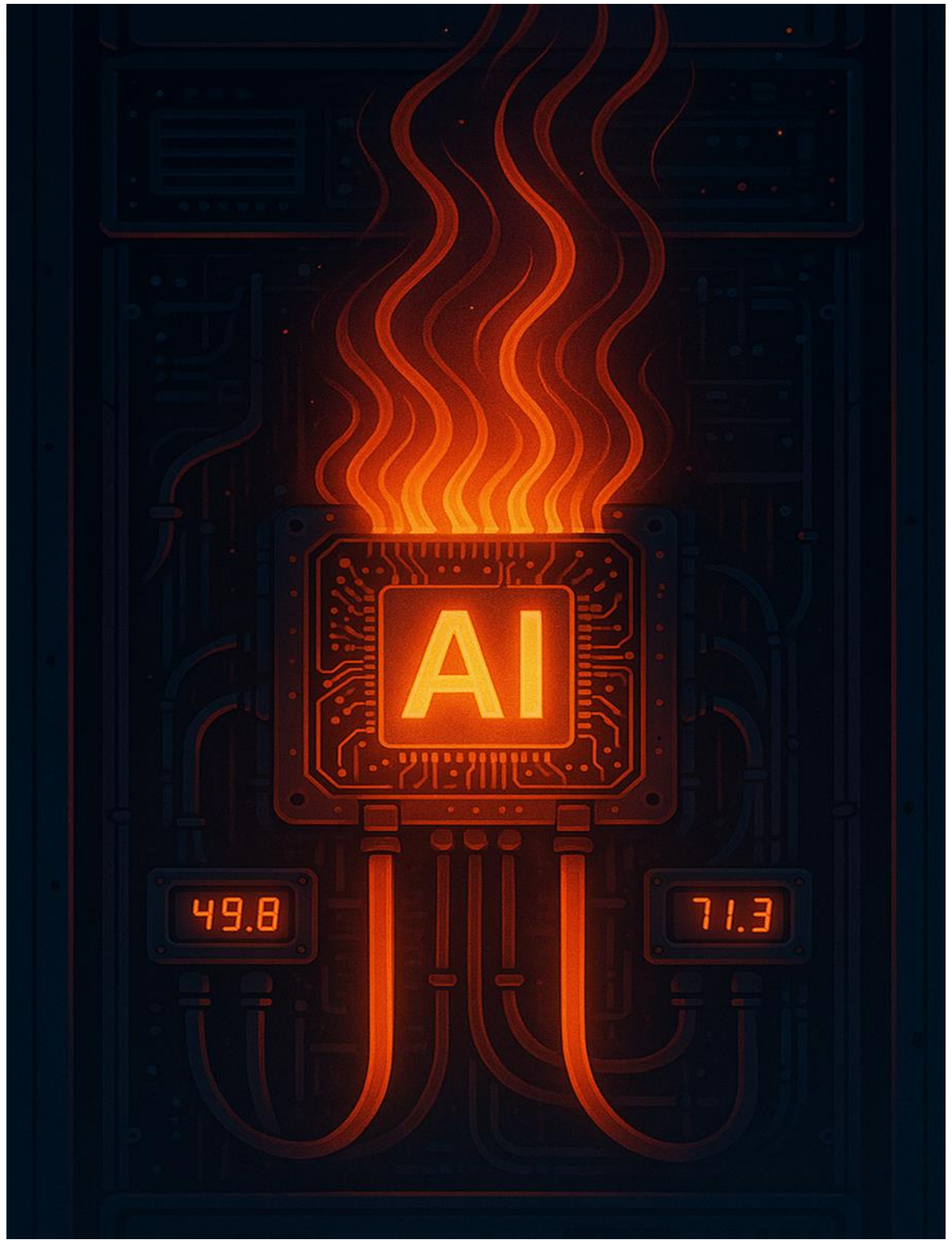
- Large Language Models (LLM) are inaccurate and fall 40% on noisy SIGINT spectra without retraining, amplifying false positives in EW.

- Pitfalls include adversarial robustness data poisoning in distributed fusion, where one compromised node skews confidence markers.
  - An added layer of modeling is needed to accurately sift through the data



You cannot just roll the dice and gamble with the AI design

Thermodynamics and Electromagnetics



- Thermodynamics is not just a constraint

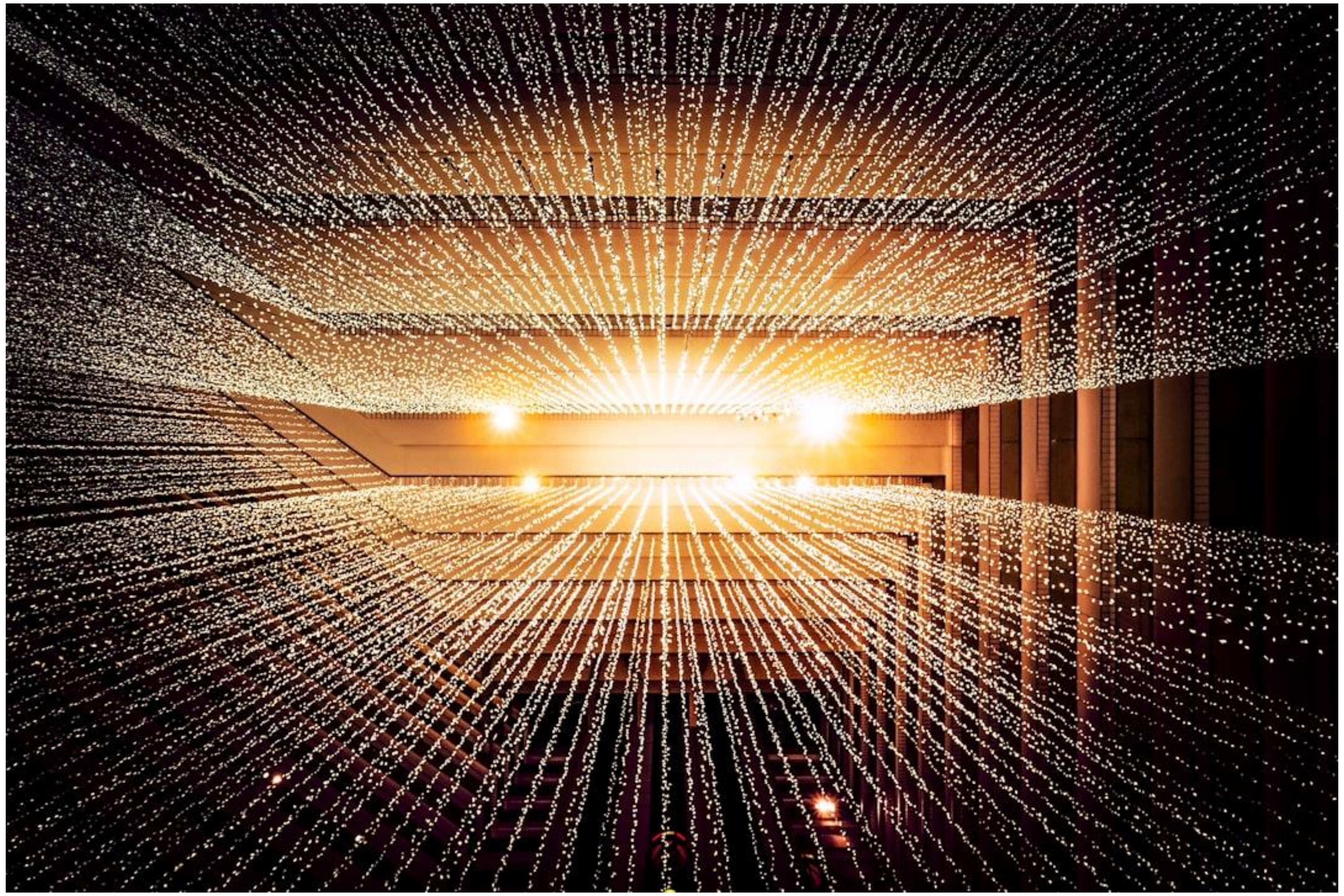
—it can be a design principle for self-organizing, energy-efficient systems.

- Thermodynamic Computing (TC)
  - systems that evolve to minimize energy dissipation and adapt dynamically to their environment. Suggests that future architectures should leverage non-equilibrium thermodynamics for adaptability and efficiency.

Light Speed : Photonics and Fiber

Photons don’t suffer resistive heating like electrons do

Research prototypes of optical matrix multipliers show potential orders-of-magnitude energy savings.



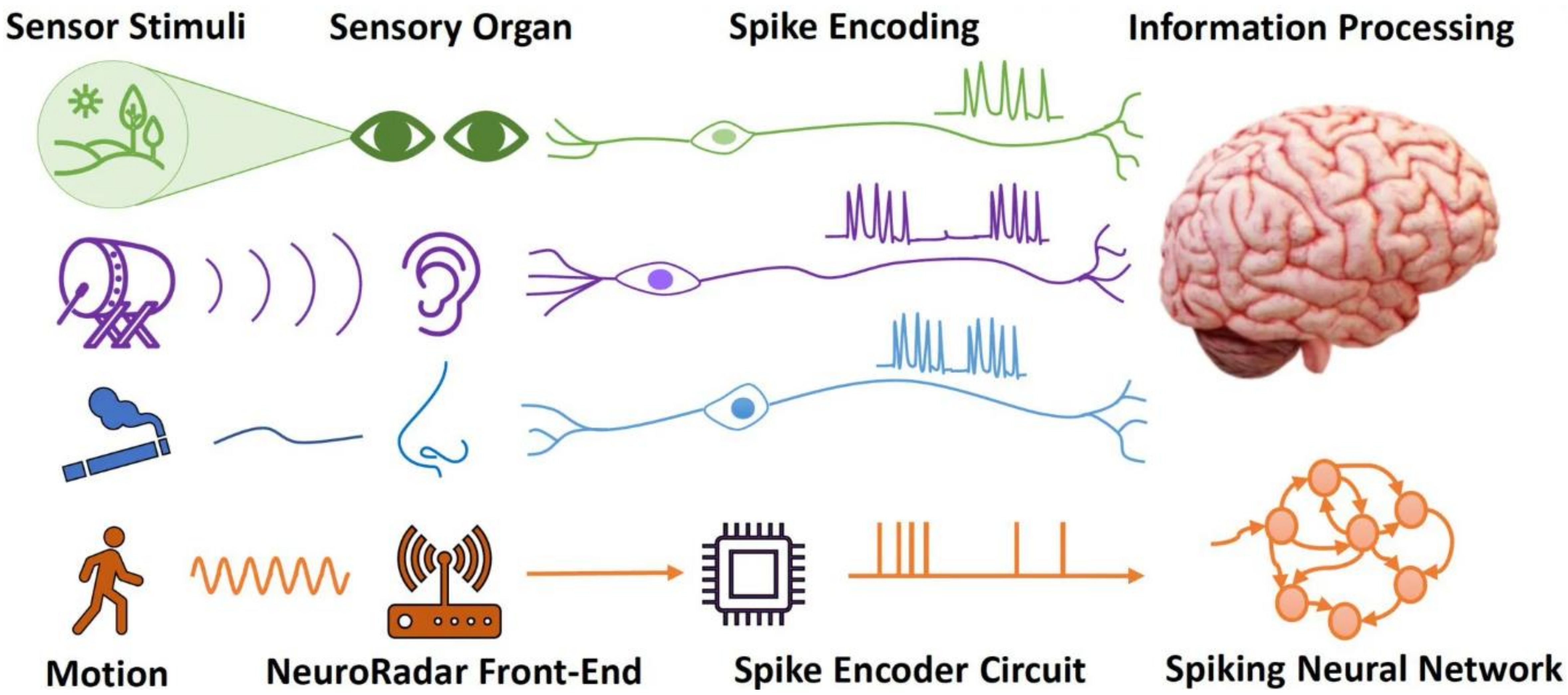
Neuromorphic Architecture

Neural architecture search (NAS)

- Automates the discovery of model architectures
- Accurate and efficient computation
- Runs cooler without sacrificing effectiveness

Sparse-Spiking Encoding

- High-fidelity asynchronous spike encoding
- Only processes <u>relevant</u> signal changes



A single-RF-chain NeuroRadar can effectively sense motion in the environment while consuming only 780µW power

Distributed Sensing and Decentralized Intelligence

Distributed sensor fusion networks process multiple sensor observations to improve reliability and confidence in measurements. Each observation includes:

- **Value** (measured data)
- **Instant** (time of measurement)
- **Confidence marker** (quality indicator)

Don't do this

Why Distributed?

- Sensors are spatially separated
- Fault tolerance
- Real-time requirements

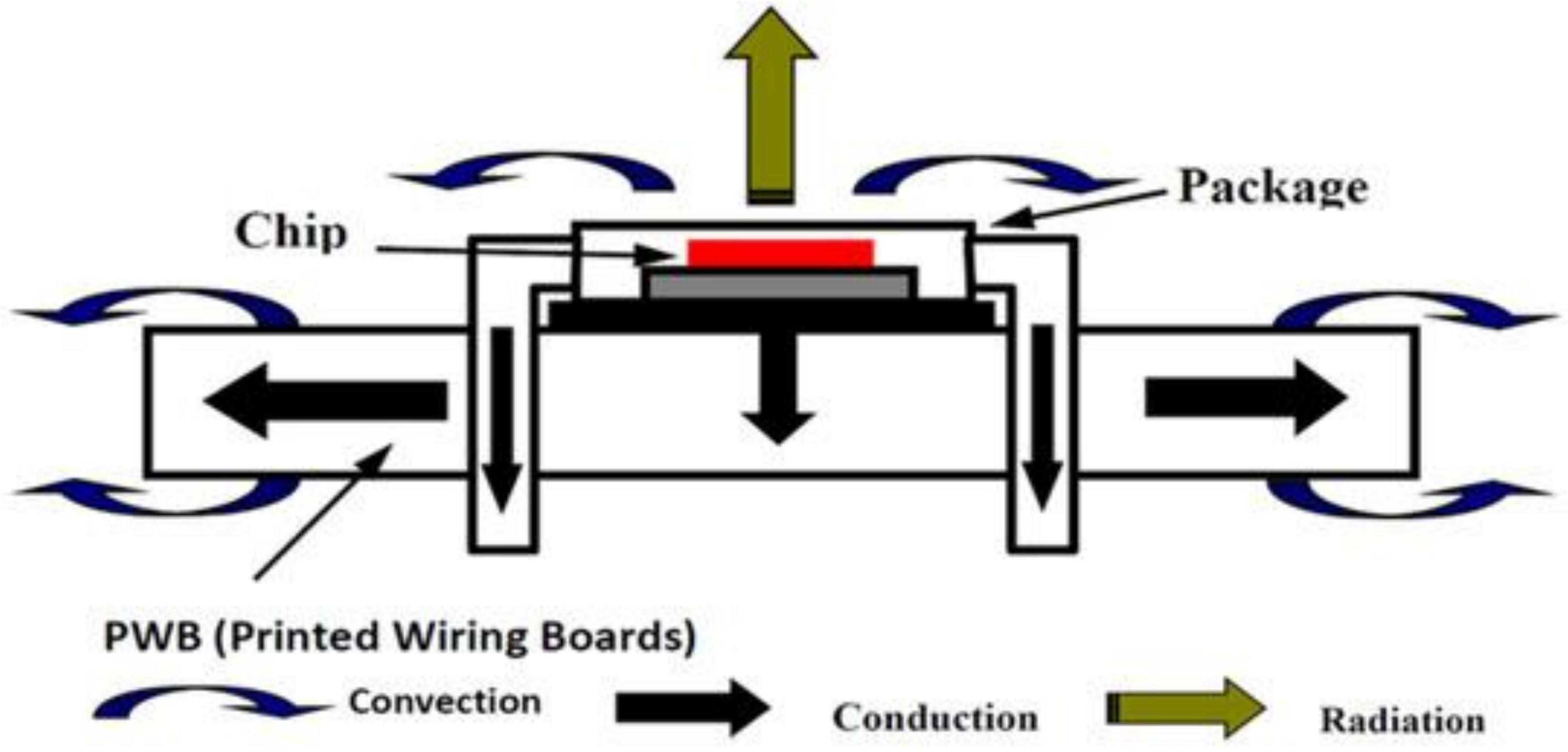
Thermal-Aware Materials

Phase change materials (PCMs).

These materials are strategically placed on or near high-power components and absorb thermal energy during operation.

When they hit their melting point, they transition from solid to liquid, absorbing large amounts of heat in the process.

Materials Considered:
FR4, Si, SiO_2, and metals with different thermal conductivities



Thermal Peak detection algorithms are implemented today on FPGA boards (And it works!)

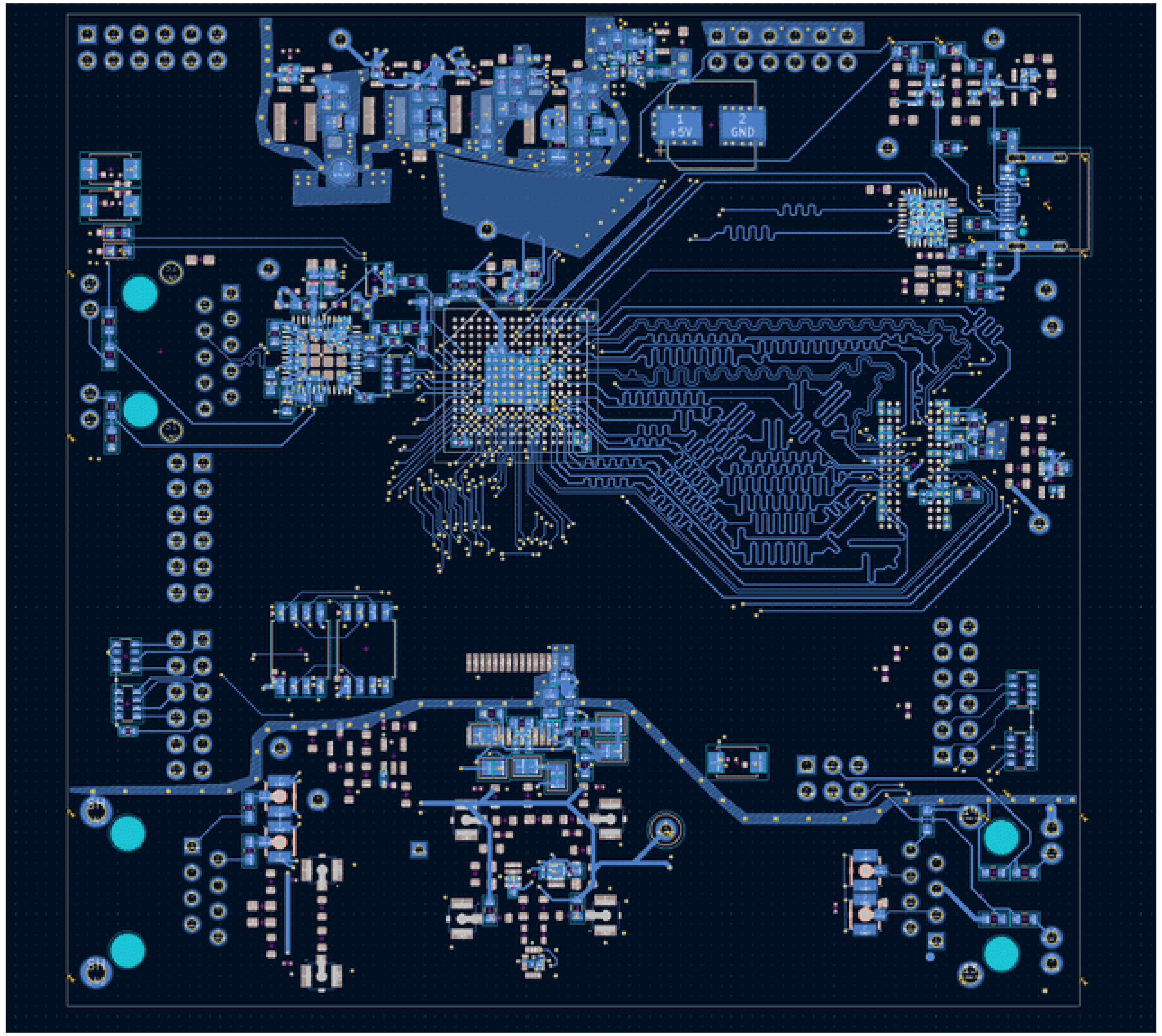
Embedded Intelligence over AI

EI design strategies classified into four levels:

- **System-level:** Task partitioning, scheduling, load balancing
- **Algorithm-level:** Binary neural networks, loop tiling
- **Architecture-level:** Custom computational primitives, pipelining
- **Technology-level:** Memristors, analog approaches

Five key metrics for EI architectures:

- Fast training time
- Real-time decision-making
- Energy efficiency
- Low area implementation
- Scalability



FPGAs can be up to 50% more powerful and consume 30% less energy

Now, what do we do?

- Focus on **embedded intelligence**
  - Neuromorphic Architecture – mimic biology
  - Design for the mission
  - Digital Twining
- Use Thermodynamics to your advantage
  - Thermal Aware Materials
- Distribute and decentralize your sensing
  - Don’t put all your eggs in one basket!
- Use Fiber Optics whenever possible

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Questions?

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Thank you

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