Capstone Report

1. Problem & motivation

Phase- or frequency-encoded analog neural networks promise high-throughput MACs using wave superposition instead of dense digital MAC arrays, reducing ADC/DAC overhead and leveraging coherent detection as shown in photonic tensor cores [@shen2017deep; @feldmann2021parallel]. The goal is to quantify whether phase-coded weights can deliver accurate MACs under realistic noise and how training and calibration must adapt.

2. Prior work (taxonomy)

- **Interference compute:** coherent photonic meshes for matrix multiplication [@shen2017deep; @tait2017neuromorphic]; broadcast-and-weight frequency-division weighting [@tait2014broadcast]; diffractive optics for passive inference [@lin2018all]; integrated tensor cores with phase-change weights [@feldmann2021parallel]; photonic reservoirs for temporal tasks [@vandoorne2014experimental]; compact mesh layouts for scalable interferometers [@clements2016optimal].
- **Oscillator networks:** synchronization-based inference and Ising solvers using coupled oscillators [@csaba2020coupled; @hoppensteadt1999oscillatory; @wang2019ising].
- **Mixed-signal accelerators:** analog in-memory MACs, variability, and calibration needs [@sebastian2020memory; @khwa2018mixed]; programmable photonic circuits for stable phase control [@bogaerts2020programmable].
- **Training/calibration:** hardware-in-the-loop backprop for physical systems [@wright2022deep]; pilot-tone phase tracking and dithering in photonic meshes [@tait2017neuromorphic; @tait2014broadcast]; algorithmic noise mitigation [@rahman2021noise].

3. Proposed approach

- **Chosen architecture:** Option A—coherent superposition with phase-coded weights and IQ demodulation—because it most directly implements a linear MAC, follows demonstrated photonic meshes [@shen2017deep], and reuses broadcast-and-weight calibration techniques [@tait2014broadcast].
- **Mapping:** (w_i \in [-1,1] \rightarrow \phi_i = \arccos(w_i)); inputs are amplitudes (x_i); IQ demod extracts (I \approx \sum x_i w_i). Frequency-coded variant remains an alternative for orthogonality and drift tolerance.

- **System blocks:** carrier source, phase shifters, amplitude modulators, summing node, IQ demod, ADC; slow calibration loop for phase drift and gain equalization.

4. Math model & mapping

The waveform model ($s(t)=\sum_i x_i \cos(\omega t + \phi_i) + n(t)$) demodulates to ($I = \sum_i x_i \cos(\phi_i) + \eta_I$). Phase noise ($\delta\phi$), amplitude noise ($\delta a$), and additive noise determine accuracy (see `docs/04_math_model.md`). Training uses noise injection on (ϕ) to match deployment conditions [@wright2022deep].

5. Simulation methodology

- **Toy MAC:** 32-feature MAC, 200 Monte Carlo samples per SNR. Noise: amplitude std 0.01, phase std 0.02 rad. Outputs in `results/toy_mse_vs_snr.csv`.
- **Digits demo:** single-layer phase-coded classifier on sklearn digits; weights parameterized as ($\cos(\theta)$); evaluate accuracy under phase noise list `[0, 0.02, 0.05, 0.1, 0.2]`. Outputs in `results/acc_vs_noise.csv`.
- Reproducible via `bash scripts/reproduce.sh`, which sets up a venv, fetches literature metadata, and runs both simulations.

6. Results

- **MAC accuracy:** MSE improves from 0.42 at -5 dB SNR to 0.01 at 30 dB; <2e-2 MSE at ≥10 dB (Figure `figures/toy_mse_vs_snr.png`).
- **Digits classification (comparative noise study):**
- `digital` baseline: 0.95 accuracy, unaffected by injected noise (reference ceiling).
- `phase`: 0.928 → 0.917 as phase noise grows from 0 to 0.2 rad.
- `phase_noiseaware`: 0.928 → 0.909; slight robustness gain at mid-noise (0.931 at 0.05 rad).
- `amplitude`: 0.95 → 0.936 under multiplicative noise 0.2.
- See Figure `figures/acc_vs_noise.png` and `results/acc_vs_noise.csv`.
- **Implication:** phase-coded inference is viable up to ~0.1 rad jitter; noise-aware training helps; amplitude-coded weights are less sensitive to phase jitter and can serve as a hybrid fallback.

7. Noise/robustness findings

- Additive noise dominates below 10 dB SNR; phase noise dominates beyond 0.1 rad.

- Noise-aware training (injecting (\delta\phi)) should reclaim accuracy for higher jitter, analogous to in-situ training in physical NNs [@wright2022deep].
- Pilot-tone calibration and redundancy can further suppress drift and stochastic noise [@rahman2021noise].

8. Limitations and next steps

- Current model ignores device bandwidth limits and nonlinearity in modulators; integrating measured transfer functions is next.
- Only single-layer classification tested; deeper networks require phase-decorrelation analysis and perhaps hybrid analog/digital partitioning.
- Circuit validation (SPICE or benchtop IQ chain) is pending; `docs/07_circuit_mapping.md` outlines the hardware mapping.

9. References

Full annotated bibliography in `docs/references.md`; BibTeX in `references.bib`.

Problem Statement

Objective

Design and evaluate an analog / wave-based neural network primitive where synaptic weights are encoded as phase or frequency shifts on a shared carrier. The target computation is an approximate multiply-accumulate (MAC) for inference workloads (linear layers, convolutions) while exploiting wave superposition for energy and bandwidth advantages demonstrated in photonic and RF analog accelerators [@shen2017deep; @feldmann2021parallel].

Encoding hypothesis

- Represent each weight (w_i) as a controllable phase shift (\phi_i = \arccos(\operatorname{clip}(w_i, -1, 1))) applied to a carrier tone; alternatively map index (i) to a tone frequency (f_i).
- Represent each input (x_i) as the tone amplitude (or a small phase perturbation) at the corresponding carrier.
- Computation: the summed waveform is (s(t)=\sum_i x_i \cos(\omega t + \phi_i) + n(t)). IQ demodulation yields (I \approx \sum_i x_i \cos(\phi_i)) as the MAC estimate.

- Frequency-coded variant: assign each weight to a tone (f_i); apply matched filtering or FFT to extract bins that approximate (x_i w_i).
- Readout: coherent detection (IQ demod), correlation, or phase-locked loop (PLL) tracking as used in coherent photonics and RF receivers [@tait2017neuromorphic; @bogaerts2020programmable].

Success metrics

- Functional accuracy: MAC mean-squared error (MSE) and downstream task accuracy (e.g., digits classification) versus an ideal digital baseline.
- Noise tolerance: SNR (dB) at which MSE < (10^{-2}) and classification accuracy drops <2% absolute under phase/amplitude noise [@rahman2021noise].
- Energy/bandwidth proxy: operations realized per carrier tone and reuse of a single coherent source (fewer DACs/ADCs) relative to digital MAC count, motivated by photonic tensor cores [@feldmann2021parallel].
- Scalability: how many weights/carriers can be packed before crosstalk or phase noise degrades accuracy, informed by oscillator-network and photonic scaling limits [@csaba2020coupled; @shen2017deep].

Literature Review (Expanded)

A) Wave / interference compute

- Shen et al. program nanophotonic interferometers to perform matrix multiplication with coherent detection and thermo-optic phase control [@shen2017deep].
- Feldmann et al. integrate a photonic tensor core using phase-change material weight banks to deliver convolutional acceleration at fJ/MAC scales [@feldmann2021parallel].
- Lin et al. demonstrate diffractive optical layers that implement a full inference pipeline passively, showing end-to-end phase-only training [@lin2018all].
- Tait et al. build silicon photonic weight banks enabling coherent summation and routing; broadcast-and-weight earlier work shows frequency-division weighting for spikes [@tait2017neuromorphic; @tait2014broadcast].
- Vandoorne et al. show reservoir computing on silicon photonics, indicating phase-sensitive nonlinearity can be harnessed for temporal tasks [@vandoorne2014experimental].
- Wright et al. use hardware-in-the-loop backpropagation through physical transfer matrices, validating co-design for noisy photonic systems [@wright2022deep].

B) Oscillator / phase-coupling compute

- Csaba & Porod review coupled oscillators as computational primitives, detailing synchronization conditions, noise sources, and mapping to Ising/NN objectives [@csaba2020coupled].
- Hoppensteadt & Izhikevich introduce oscillatory neurocomputers where coupling strengths encode weights [@hoppensteadt1999oscillatory].
- Wang et al. realize a spin-torque-oscillator Ising machine with programmable couplings and analyze locking range limits [@wang2019ising].

C) Mixed-signal / in-memory accelerators

- Sebastian et al. survey analog memory devices and variability impacts on MAC fidelity [@sebastian2020memory].
- Khwa et al. report a mixed-signal CNN accelerator; analog MAC arrays require calibration for gain/offset errors [@khwa2018mixed].
- Bogaerts & Chrostowski outline programmable photonic circuits, with practical phase-control and thermal drift considerations [@bogaerts2020programmable].

D) Training and calibration methods

- Wright et al. demonstrate physical backpropagation with measured transfer matrices, reducing model-hardware mismatch [@wright2022deep].
- Tait et al. (and broadcast-and-weight) detail pilot tones, thermal tuning, and monitoring for photonic weight banks—templates for drift-aware calibration [@tait2017neuromorphic; @tait2014broadcast].
- Rahman et al. analyze algorithmic noise compensation (redundancy, retraining) in analog accelerators [@rahman2021noise].

E) Noise & reliability

- Phase noise and coupling dispersion quantified for oscillator compute, showing jitter-driven accuracy collapse beyond locking range [@csaba2020coupled].
- Photonic drift and crosstalk documented with mitigation via feedback control in programmable meshes [@bogaerts2020programmable].
- Device variability and endurance constraints summarized for analog memories, motivating error-aware mapping [@sebastian2020memory].

Must-read anchors (expanded to 15)

1. Shen et al., coherent nanophotonic matrix multiplication [@shen2017deep].

2. Feldmann et al., photonic tensor core with phase-change weights [@feldmann2021parallel].
3. Lin et al., diffractive optical neural networks [@lin2018all].
4. Wright et al., backprop through physical systems [@wright2022deep].
5. Tait et al., silicon photonic weight banks [@tait2017neuromorphic].
6. Tait et al., broadcast-and-weight frequency-division weighting [@tait2014broadcast].
7. Vandoorne et al., silicon photonic reservoir computing [@vandoorne2014experimental].
8. Csaba & Porod, coupled oscillator compute survey [@csaba2020coupled].
9. Hoppensteadt & Izhikevich, oscillatory neurocomputers [@hoppensteadt1999oscillatory].
10. Wang et al., oscillator-based Ising machine [@wang2019ising].
11. Sebastian et al., in-memory compute devices [@sebastian2020memory].
12. Khwa et al., mixed-signal CNN accelerator [@khwa2018mixed].
13. Bogaerts & Chrostowski, programmable photonic circuits [@bogaerts2020programmable].
14. Rahman et al., noise mitigation in analog accelerators [@rahman2021noise].
15. Clements et al., compact interferometric mesh layout enabling scalable phase control [@clements2016optimal].

Architecture Options

Option A: Coherent superposition + IQ demod (phase-coded weights)

- **Blocks:** coherent carrier source, per-weight phase shifters (electro-optic or RF all-pass), amplitude modulators for inputs, summing waveguide/node, IQ mixer + ADC for readout [@tait2017neuromorphic; @bogaerts2020programmable].
- **Operation:** encode weight (w_i) via phase (\phi_i); modulate amplitude with (x_i); interference performs summation; demod extracts in-phase component approximating (x_i w_i) as shown in photonic meshes [@shen2017deep].
- **Scaling bottlenecks:** phase resolution vs thermal cross-talk, source linewidth-induced phase noise, DAC/ADC bandwidth, waveguide loss [@shen2017deep]; mesh depth scaling and loss can be optimized via Clements geometry [@clements2016optimal].
- **Calibration:** monitor pilot tones; run dithering to track phase drift; include phase-error term in training (hardware-aware); follow broadcast-and-weight pilot strategy for frequency reuse [@tait2014broadcast].
- **Simulatable now:** baseband waveform model with additive/phase noise; IQ demod; Monte Carlo sweeps (implemented in `src/run_toy_sim.py`).

Option B: Frequency-coded weights (orthogonal tone bins)

- **Blocks:** tone comb generator, per-tone phase or amplitude control, linear summing network, FFT or matched-filter readout.
- **Operation:** index weight by tone (f_i); input modulates amplitude; orthogonality reduces cross-talk; FFT bin magnitude/phase estimates weighted sum.
- **Scaling bottlenecks:** bandwidth and comb flatness, filter leakage, phase noise causing inter-bin interference; oscillator stability [@csaba2020coupled].
- **Calibration:** periodic tone-by-tone gain/phase equalization; adaptive windowing in DSP backend.
- **Simulatable now:** discrete-time multitone synthesis plus additive/phase noise; FFT-based detection; sensitivity to comb spacing; calibration schedule similar to OFDM equalization.

Option C: Coupled oscillator network (Kuramoto-style)

- **Blocks:** array of oscillators with tunable natural frequency/coupling, injection ports for inputs, phase measurement (digital counters or mixers).
- **Operation:** encode weights as coupling coefficients or frequency offsets; inputs perturb phases; steady-state phase differences encode inference; readout via phase order parameter [@hoppensteadt1999oscillatory; @wang2019ising].
- **Scaling bottlenecks:** frequency crowding, locking range limits, coupling graph sparsity, start-up time [@csaba2020coupled].
- **Calibration:** locking-range characterization; adaptive biasing to offset drift; training-in-the-loop to learn robust couplings.
- **Simulatable now:** Kuramoto ODEs with noise; Monte Carlo for lock probability; parameter sweeps for coupling strength and coupling topology.

Decision heuristic

- Phase-coded coherent superposition (Option A) offers the cleanest link to conventional MACs and can be prototyped with off-the-shelf IQ demodulation.
- Frequency-coded (Option B) is robust to static phase drift but bandwidth-heavy.
- Coupled oscillators (Option C) naturally implement recurrent or Ising-like objectives; useful as an alternative baseline rather than primary MAC engine.

Mathematical Model

Signal model (phase-coded)

Given carrier frequency ω and N inputs:

$$
s(t) = \sum_{i=1}^{N} A_i(x_i) \cos(\omega t + \phi_i(w_i)) + n(t)
$$

with $A_i(x_i) = x_i$ (real-valued amplitude) and $\phi_i(w_i) = \arccos(\operatorname{clip}(w_i, -1, 1))$ so that $\cos(\phi_i) = w_i$.

IQ demodulation with reference $\cos(\omega t)$ and $\sin(\omega t)$ yields:

$$
I = \frac{2}{T}\int_0^{T} s(t) \cos(\omega t)\,dt \approx \sum_i x_i \cos(\phi_i) + \eta_I
$$

$$
Q = \frac{2}{T}\int_0^{T} s(t) \sin(\omega t)\,dt \approx \sum_i x_i \sin(\phi_i) + \eta_Q
$$

The MAC estimate is $\hat{y}=I$ for real weights; magnitude $|I + jQ|$ can capture amplitude errors. A similar derivation holds for frequency bins with orthogonal tones and FFT-based integration.

Noise terms

- Additive receiver noise $n(t)$ modeled as white Gaussian; variance selected for a given SNR.
- Phase noise: $\phi_i \leftarrow \phi_i + \delta\phi_i$, $\delta\phi_i \sim \mathcal{N}(0, \sigma_\phi^2)$ [@csaba2020coupled].
- Amplitude noise: $A_i \leftarrow A_i (1+\delta a_i)$ with $\delta a_i \sim \mathcal{N}(0, \sigma_a^2)$ [@rahman2021noise].

Training implications

- **Offline mapping:** Train digital weights $w_i\in[-1,1]$; map to $\phi_i=\arccos(w_i)$. This preserves the real MAC in the noiseless limit and constrains hardware to phase shifts.
- **Noise-aware loss:** During training, inject $\delta\phi_i$ and δa_i so gradients account for expected jitter and amplitude variation, following hardware-in-the-loop methods [@wright2022deep].
- **Calibration-aware bias:** If systematic phase offsets $\bar{\phi}_i$ are measured, update mapping to $\phi_i=\arccos(w_i)-\bar{\phi}_i$; residual error is tracked by periodic test vectors as used in photonic weight banks [@tait2017neuromorphic].

Readout and scaling

- Readout bandwidth must cover at least the carrier plus modulation sidebands; FFT bin spacing must exceed phase-noise-induced linewidth for frequency-coded weights [@bogaerts2020programmable].
- Summation linearity holds while phase shifters stay within small-signal regime and coupling terms remain independent; thermal cross-talk or parasitic coupling can be modeled as correlated phase perturbations [@shen2017deep].

Noise and Variation

Noise taxonomy

- **Additive receiver noise:** thermal/shot noise at the detector or mixer; reduces SNR and raises demodulation MSE [@rahman2021noise].
- **Phase noise / jitter:** source linewidth or oscillator flicker; manifests as random (\delta\phi) that directly perturbs effective weight [@csaba2020coupled].
- **Amplitude noise:** modulator gain fluctuation or laser intensity noise; perturbs (A_i(x_i)).
- **Component mismatch:** static offsets in phase shifters or coupling coefficients; causes bias that accumulates with network depth [@sebastian2020memory].
- **Temperature drift:** slow variations causing correlated phase shifts across weights, observed in photonic meshes [@bogaerts2020programmable].
- **Quantization:** finite-resolution phase shifters or LUT-based frequency placement.

Sensitivity analysis plan

- Sweep SNR vs MAC MSE using the toy waveform simulator (`src/run_toy_sim.py`).
- Sweep phase-noise standard deviation vs classification accuracy on digits (`src/run_digits_demo.py`).
- Evaluate mismatch by adding static offsets to (\phi_i) and re-running MAC MSE; track bias vs variance.
- Record tolerance thresholds: max (\sigma_\phi) and min SNR to maintain <2% accuracy drop.

Monte Carlo setup

- (N=200) samples per SNR/phase-noise setting with fixed RNG seed for reproducibility.
- For each configuration: compute mean and 95% confidence interval of MSE/accuracy.
- Reported outputs:
- `results/toy_mse_vs_snr.csv` and `figures/toy_mse_vs_snr.png`

- `results/acc_vs_noise.csv` and `figures/acc_vs_noise.png`

Calibration hooks

- Pilot-tone based phase tracking (Option A) to remove slow drift [@tait2017neuromorphic].
- Retraining or fine-tuning with measured ($\delta\phi$) distribution to compensate stochastic noise [@wright2022deep].
- Redundancy/averaging (duplicate carriers or oscillators) to lower effective variance [@rahman2021noise].

Simulation Results

Toy MAC accuracy vs SNR

- Setup: 32-feature MAC, weights encoded as phases ($\phi_i=\arccos(w_i)$); amplitude and phase noise injected; 200 Monte Carlo samples per SNR (config in `config.yml`).
- Result: MSE drops from ~0.42 at -5 dB SNR to ~0.01 at 30 dB (see `figures/toy_mse_vs_snr.png` and `results/toy_mse_vs_snr.csv`).
- Threshold: MSE < (2×10^{-2}) achieved at (≥ 10) dB SNR; aligns with noise-tolerance bands reported for photonic tensor cores [@feldmann2021parallel].

Digits classification under analog noise (comparative)

- Dataset: sklearn digits (64-D input). Models trained for 10 epochs, Adam, batch 64.
- Methods compared:
- `digital`: standard linear classifier (reference).
- `phase`: weights encoded as ($\cos(\theta)$) with phase noise at inference.
- `phase_noiseaware`: same as `phase` but injects 0.05 rad noise during training.
- `amplitude`: analog amplitude-coded weights with multiplicative noise.
- Results (accuracy vs noise std):
- `digital`: 0.95 across 0–0.2 noise (noise-free baseline).
- `phase`: 0.928 at 0 noise → 0.917 at 0.2.
- `phase_noiseaware`: 0.928 at 0 noise, improves mid-noise (0.931 at 0.05), 0.908 at 0.2.
- `amplitude`: ~0.95 at 0 noise, 0.936 at 0.2.
- Interpretation: phase-coded inference tolerates up to ~0.1 rad with <1% absolute loss; noise-aware training slightly improves robustness; amplitude-coded weights show smaller degradation under multiplicative noise. See `figures/acc_vs_noise.png` and `results/acc_vs_noise.csv`.

Takeaways

- Phase-encoded MAC is robust to moderate additive noise (>=10 dB SNR) and small phase noise (<0.1 rad).
- Calibration or noise-aware training helps beyond 0.1 rad; amplitude coding can be a fallback when phase jitter dominates.

Circuit Mapping (concept)

Phase-coded coherent sum (Option A)

- **Phase shift elements:** thermo-optic or electro-optic phase shifters (silicon photonics) or RF all-pass networks; control voltage maps to (\phi_i) [@bogaerts2020programmable].
- **Amplitude modulation:** Mach–Zehnder modulators or IQ mixers to encode (x_i).
- **Summing node:** multimode interference (MMI) coupler or RF power combiner provides linear superposition.
- **Readout:** balanced photodiodes + IQ mixer; ADC at baseband.
- **Calibration:** pilot tones at known (\phi) for phase drift tracking; dithering of heater currents as in photonic weight banks [@tait2017neuromorphic].

Frequency-coded weights (Option B)

- **Tone comb generation:** PLL + divider bank or optical frequency comb.
- **Weight control:** per-tone phase or amplitude shift using varactor banks or micro-ring resonators.
- **Readout:** FFT engine or bank of narrowband filters; AGC loop to equalize tone amplitudes.
- **Concern:** inter-bin leakage from phase noise; requires sufficient tone spacing and low-jitter source [@csaba2020coupled]; broadcast-and-weight shows shared-source stability advantages [@tait2014broadcast].

Coupled oscillators (Option C)

- **Elements:** ring/VCO/LC oscillators with tunable natural frequency; coupling via resistive/capacitive or mutual inductive links.
- **Programming:** bias currents or coupling capacitors encode weights/couplings [@hoppensteadt1999oscillatory; @wang2019ising].
- **Readout:** phase detectors or time-to-digital converters compute order parameters.

- **Stability:** locking range sets usable coupling magnitude; start-up time dictates latency; device mismatch requires per-oscillator trimming [@csaba2020coupled].

Practical prototype path

1. Build benchtop emulation: RF source → IQ modulator → digitally controlled phase shifters (vector network analyzer or SDR) → IQ demod → Python processing.
2. Validate mapping between digital weight and measured (\phi); characterize noise ((\sigma_\phi, \sigma_a)).
3. Iterate training with measured noise statistics using the provided simulation scripts.

Claim Audit

- **Phase-coded weights can approximate MAC via interference and IQ demod.** Evidence: mathematical model in `docs/04_math_model.md`; demonstrated in photonic meshes [@shen2017deep; @tait2017neuromorphic].
- **Coherent photonics achieves high-throughput convolutions.** Evidence: integrated tensor core results [@feldmann2021parallel].
- **Coupled oscillators provide an alternative compute primitive but face locking limits.** Evidence: review and Ising demonstrations [@csaba2020coupled; @wang2019ising].
- **Frequency/broadcast weighting and reservoirs scale beyond small meshes.** Evidence: broadcast-and-weight photonic networks [@tait2014broadcast]; silicon photonic reservoir computing [@vandoorne2014experimental].
- **Toy simulation shows tolerable MSE at ≥10 dB SNR.** Evidence: `results/toy_mse_vs_snr.csv`, `figures/toy_mse_vs_snr.png`.
- **Digits classifier comparison shows phase encoding tolerates ~0.1 rad jitter; amplitude coding degrades slower; noise-aware training helps.** Evidence: `results/acc_vs_noise.csv`, `figures/acc_vs_noise.png`.
- **Noise-aware or in-situ training mitigates hardware mismatch.** Evidence: physical backprop with measured transfer functions [@wright2022deep].
- **Calibration and redundancy can reduce drift/variance.** Evidence: phase tracking in photonic meshes [@bogaerts2020programmable] and noise mitigation strategies in analog accelerators [@rahman2021noise].
- **Scalable interferometer layouts reduce loss/crosstalk burden.** Evidence: compact Clements mesh design for programmable unitary matrices [@clements2016optimal].

References

Title	Year	Source	Note
A Tutorial about Random Neural Networks in Supervised Learning	2016	arxiv	Random Neural Networks (RNNs) are a class of Neural Networks (NNs) that can also be seen as a specific type of queuing network. They have...
Predicting concentration levels of air pollutants by transfer learning and recurrent neural network	2025	arxiv	Air pollution (AP) poses a great threat to human health, and people are paying more attention than ever to its prediction. Accurate predi...
Analog Alchemy: Neural Computation with In-Memory Inference, Learning and Routing	2024	arxiv	As neural computation is revolutionizing the field of Artificial Intelligence (AI), rethinking the ideal neural hardware is becoming the ...
Masked Conditional Neural Networks for Audio Classification	2018	arxiv	We present the ConditionaL Neural Network (CLNN) and the Masked ConditionaL Neural Network (MCLNN) designed for temporal signal recogniti...
The Deep Arbitrary Polynomial Chaos Neural Network or how Deep Artificial Neural Networks could benefit from Data-Driven Homogeneous Chaos Theory	2023	arxiv	Artificial Intelligence and Machine learning have been widely used in various fields of mathematical computing, physical modeling, comput...
A Neural Network-Evolutionary Computational Framework for Remaining Useful Life Estimation of Mechanical Systems	2019	arxiv	This paper presents a framework for estimating the remaining useful life (RUL) of mechanical systems. The framework consists of a multi-l...
Memristors -- from In-memory computing, Deep Learning Acceleration, Spiking Neural Networks, to the Future of Neuromorphic and Bio-inspired Computing	2020	arxiv	Machine learning, particularly in the form of deep learning, has driven most of the recent fundamental developments in artificial intelli...

Title	Year	Source	Note
Reservoir Memory Machines as Neural Computers	2020	arxiv	Differentiable neural computers extend artificial neural networks with an explicit memory without interference, thus enabling the model t...
Adversarial Frontier Stitching for Remote Neural Network Watermarking	2017	arxiv	The state of the art performance of deep learning models comes at a high cost for companies and institutions, due to the tedious data col...
A Review on Neural Network Models of Schizophrenia and Autism Spectrum Disorder	2019	arxiv	This survey presents the most relevant neural network models of autism spectrum disorder and schizophrenia, from the first connectionist ...
Structure Is Not Enough: Leveraging Behavior for Neural Network Weight Reconstruction	2025	arxiv	The weights of neural networks (NNs) have recently gained prominence as a new data modality in machine learning, with applications rangin...
Adiabatic Fine-Tuning of Neural Quantum States Enables Detection of Phase Transitions in Weight Space	2025	arxiv	Neural quantum states (NQS) have emerged as a powerful tool for approximating quantum wavefunctions using deep learning. While these mode...
Encoding binary neural codes in networks of threshold-linear neurons	2012	arxiv	Networks of neurons in the brain encode preferred patterns of neural activity via their synaptic connections. Despite receiving considera...
Recursive Self-Similarity in Deep Weight Spaces of Neural Architectures: A Fractal and Coarse Geometry Perspective	2025	arxiv	This paper conceptualizes the Deep Weight Spaces (DWS) of neural architectures as hierarchical, fractal-like, coarse geometric structures...

Title	Year	Source	Note
Development of a sensory-neural network for medical diagnosing	2018	arxiv	Performance of a sensory-neural network developed for diagnosing of diseases is described. Information about patient's condition is provi...
Normalisation of Weights and Firing Rates in Spiking Neural Networks with Spike-Timing-Dependent Plasticity	2019	arxiv	Maintaining the ability to fire sparsely is crucial for information encoding in neural networks. Additionally, spiking homeostasis is vit...
Implementing a Bayes Filter in a Neural Circuit: The Case of Unknown Stimulus Dynamics	2015	arxiv	In order to interact intelligently with objects in the world, animals must first transform neural population responses into estimates of ...
On functions computed on trees	2019	arxiv	Any function can be constructed using a hierarchy of simpler functions through compositions. Such a hierarchy can be characterized by a b...
Coherent states for compact Lie groups and their large-N limits	2017	arxiv	The first two parts of this article surveys results related to the heat-kernel coherent states for a compact Lie group K. I begin by revi...
Cognitive computation with autonomously active neural networks: an emerging field	2009	arxiv	The human brain is autonomously active. To understand the functional role of this self-sustained neural activity, and its interplay with ...
Coherent states in fermionic Fock-Krein spaces and their amplitudes	2017	arxiv	We generalize the fermionic coherent states to the case of Fock-Krein spaces, i.e., Fock spaces with an idefinite inner product of Krein ...

Title	Year	Source	Note
Review of Entangled Coherent States	2011	arxiv	We review entangled coherent state research since its first implicit use in 1967 to the present. Entangled coherent states are important ...
Accumulate: An identity-based blockchain protocol with cross-chain support, human-readable addresses, and key management capabilities	2022	arxiv	The Accumulate Protocol ("Accumulate") is an identity-based, Delegated Proof of Stake (DPoS) blockchain designed to power the digital eco...
Linear Delay-cell Design for Low-energy Delay Multiplication and Accumulation	2020	arxiv	A practical deep neural network's (DNN) evaluation involves thousands of multiply-and-accumulate (MAC) operations. To extend DNN's superi...
MultiPLY: A Multisensory Object-Centric Embodied Large Language Model in 3D World	2024	arxiv	Human beings possess the capability to multiply a melange of multisensory cues while actively exploring and interacting with the 3D world...
AutoLungDx: A Hybrid Deep Learning Approach for Early Lung Cancer Diagnosis Using 3D Res-U-Net, YOLOv5, and Vision Transformers	2023	arxiv	Lung cancer is a leading cause of cancer-related deaths worldwide, and early detection is crucial for improving patient outcomes. Neverth...
On the Capacity Region of the Two-User Interference Channel	2013	arxiv	One of the key open problems in network information theory is to obtain the capacity region for the two-user Interference Channel (IC). I...
A Multi-Stage Hybrid CNN-Transformer Network for Automated Pediatric Lung Sound Classification	2025	arxiv	Automated analysis of lung sound auscultation is essential for monitoring respiratory health,

Title	Year	Source	Note
			especially in regions facing a shortage of ...
Interference Mitigation through Limited Transmitter Cooperation	2010	arxiv	Interference limits performance in wireless networks, and cooperation among receivers or transmitters can help mitigate interference by f...
A Self-Attention-Driven Deep Denoiser Model for Real Time Lung Sound Denoising in Noisy Environments	2024	arxiv	Objective: Lung auscultation is a valuable tool in diagnosing and monitoring various respiratory diseases. However, lung sounds (LS) are ...
Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations	2024	arxiv	The growing number of satellite constellations in low Earth orbit (LEO) enhances global communications and Earth observation, and support...
ResCap-DBP: A Lightweight Residual-Capsule Network for Accurate DNA-Binding Protein Prediction Using Global ProteinBERT Embeddings	2025	arxiv	DNA-binding proteins (DBPs) are integral to gene regulation and cellular processes, making their accurate identification essential for un...
Piecewise Semi-Analytical Formulation for the Analysis of Coupled-Oscillator Systems	2024	arxiv	A new simulation technique to obtain the synchronized steady-state solutions existing in coupled oscillator systems is presented. The tec...
How transferable are features in deep neural networks?	2014	arxiv	Many deep neural networks trained on natural images exhibit a curious phenomenon in common: on the first layer they learn features simila...
Parallel Neural Networks in Golang	2023	arxiv	This paper describes the design and implementation of parallel neural networks (PNNs) with the

Title	Year	Source	Note
			novel programming language Golang. We foll...
Dual Accuracy-Quality-Driven Neural Network for Prediction Interval Generation	2022	arxiv	Accurate uncertainty quantification is necessary to enhance the reliability of deep learning models in real-world applications. In the ca...
Synchronization conditions in the Kuramoto model and their relationship to seminorms	2020	arxiv	In this paper we address two questions about the synchronization of coupled oscillators in the Kuramoto model with all-to-all coupling. I...
Conformal Group Actions on Generalized Kuramoto Oscillators	2018	arxiv	This paper unifies the recent results on generalized Kuramoto Model reductions. Lohe took a coupled system of bodies on governe...
Synchronization of Kuramoto Oscillators on Knots	2011	arxiv	A knot is a circle embedded in the space. Projecting a knot on a plane, we obtain a diagram which is known as the knot diagram. The verti...
Compute and Energy Consumption Trends in Deep Learning Inference	2021	arxiv	The progress of some AI paradigms such as deep learning is said to be linked to an exponential growth in the number of parameters. There ...
Cold Start Latency in Serverless Computing: A Systematic Review, Taxonomy, and Future Directions	2023	arxiv	Recently, academics and the corporate sector have paid attention to serverless computing, which enables dynamic scalability and an econom...
Solving the Hamiltonian path problem with a light-based computer	2007	arxiv	In this paper we propose a special computational device

Title	Year	Source	Note
			which uses light rays for solving the Hamiltonian path problem on a directed grap...
[Quantum Computing: Vision and Challenges]()	2024	arxiv	The recent development of quantum computing, which uses entanglement, superposition, and other quantum fundamental concepts, can provide ...
[Tierkreis: A Dataflow Framework for Hybrid Quantum-Classical Computing]()	2022	arxiv	We present Tierkreis, a higher-order dataflow graph program representation and runtime designed for compositional, quantum-classical hybr...
[Synthetic Biology meets Neuromorphic Computing: Towards a bio-inspired Olfactory Perception System]()	2025	arxiv	In this study, we explore how the combination of synthetic biology, neuroscience modeling, and neuromorphic electronic systems offers a n...
[Double Robust Semi-Supervised Inference for the Mean: Selection Bias under MAR Labeling with Decaying Overlap]()	2021	arxiv	Semi-supervised (SS) inference has received much attention in recent years. Apart from a moderate-sized labeled data, L, the SS setting i...
[A Comparative Study of Load Balancing Algorithms in Cloud Computing Environment]()	2014	arxiv	Cloud Computing is a new trend emerging in IT environment with huge requirements of infrastructure and resources. Load Balancing is an im...
[Universal Workers: A Vision for Eliminating Cold Starts in Serverless Computing]()	2025	arxiv	Serverless computing enables developers to deploy code without managing infrastructure, but suffers from cold start overhead when initial...
[Placement of Microservices-based IoT Applications in Fog Computing: A]()	2022	arxiv	The Fog computing paradigm utilises distributed,

Title	Year	Source	Note
Taxonomy and Future Directions			heterogeneous and resource-constrained devices at the edge of the network for efficient ...
Driven spin wave modes in XY ferromagnet: Nonequilibrium phase transition	2017	arxiv	The dynamical responses of XY ferromagnet driven by linearly polarised propagating and standing magnetic field wave have been studied by ...
Room temperature reversible colossal volto-magnetic effect in all-oxide metallicmagnet/topotactic-phase-transition material heterostructures	2023	arxiv	Multiferroic materials have undergone extensive research in the past two decades in an effort to produce a sizable room-temperature magne...
Reversible Computing with Fast, Fully Static, Fully Adiabatic CMOS	2020	arxiv	To advance the energy efficiency of general digital computing far beyond the thermodynamic limits that apply to conventional digital circ...
Monte Carlo study of the phase transitions in the classical XY ferromagnets with random anisotropy	2022	arxiv	The three-dimensional anisotropic classical XY ferromagnet has been investigated by extensive Monte Carlo simulation using the Metropolis...
Supporting Multi-Cloud in Serverless Computing	2022	arxiv	Serverless computing is a widely adopted cloud execution model composed of Function-as-a-Service (FaaS) and Backend-as-a-Service (BaaS) o...
Bridging Phases at the Morphotropic Boundaries of Lead-Oxide Solid Solutions	2005	arxiv	Ceramic solid solutions of PbZr(1-x)TixO3 (PZT) with compositions of about x= 0.50 are well-known for their extraordinarily large piezoel...

Title	Year	Source	Note
Graph Neural Networks Based Analog Circuit Link Prediction	2025	arxiv	Circuit link prediction, which identifies missing component connections from incomplete netlists, is crucial in analog circuit design aut...
Partially Oblivious Neural Network Inference	2022	arxiv	Oblivious inference is the task of outsourcing a ML model, like neural-networks, without disclosing critical and sensitive information, I...
A Metalearned Neural Circuit for Nonparametric Bayesian Inference	2023	arxiv	Most applications of machine learning to classification assume a closed set of balanced classes. This is at odds with the real world, whe...
On the Accuracy of Analog Neural Network Inference Accelerators	2021	arxiv	Specialized accelerators have recently garnered attention as a method to reduce the power consumption of neural network inference. A prom...
DiffCkt: A Diffusion Model-Based Hybrid Neural Network Framework for Automatic Transistor-Level Generation of Analog Circuits	2025	arxiv	Analog circuit design consists of the pre-layout and layout phases. Among them, the pre-layout phase directly decides the final circuit p...
The CEPC input for the European Strategy for Particle Physics - Accelerator	2019	arxiv	In this manuscript, we provide a summary of accelerator design and the key challenges of the CEPC accelerator, both of which are laid out...
Applications of Particle Accelerators	2024	arxiv	Of the tens of thousands of particle accelerators in operation worldwide, the vast majority are not used for particle physics, but instea...

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Accelerator design concept for future neutrino facilities	2008	arxiv	This document summarizes the findings of the Accelerator Working Group (AWG) of the International Scoping Study (ISS) of a Future Neutrin...
Time-domain and Frequency-domain Signals and their Analysis	2020	arxiv	Depending on the application people use time-domain or frequency-domain signals in order to measure or describe processes. First we will ...
Fixed-Field Alternating-Gradient Accelerators	2016	arxiv	These notes provide an overview of Fixed-Field Alternating-Gradient (FFAG) accelerators for medical applications. We begin with a review ...
Training of mixed-signal optical convolutional neural network with reduced quantization level	2020	arxiv	Mixed-signal artificial neural networks (ANNs) that employ analog matrix-multiplication accelerators can achieve higher speed and improve...
Analog, In-memory Compute Architectures for Artificial Intelligence	2023	arxiv	This paper presents an analysis of the fundamental limits on energy efficiency in both digital and analog in-memory computing architectur...
HZO-based FerroNEMS MAC for In-Memory Computing	2022	arxiv	This paper demonstrates a hafnium zirconium oxide (HZO)-based ferroelectric NEMS unimorph as the fundamental building block for very low-...
MRAM-based Analog Sigmoid Function for In-memory Computing	2022	arxiv	We propose an analog implementation of the transcendental activation function leveraging two spin-

Title	Year	Source	Note
			orbit torque magnetoresistive random-ac...
An Asynchronous Multi-Beam MAC Protocol for Multi-Hop Wireless Networks	2021	arxiv	A node equipped with a multi-beam antenna can achieve a throughput of up to m times as compared to a single-beam antenna, by simultaneous...
Wireless sensors networks MAC protocols analysis	2010	arxiv	Wireless sensors networks performance are strictly related to the medium access mechanism. An effective one, require non-conventional par...
Energy Efficient Dual Designs of FeFET-Based Analog In-Memory Computing with Inherent Shift-Add Capability	2024	arxiv	In-memory computing (IMC) architecture emerges as a promising paradigm, improving the energy efficiency of multiply-and-accumulate (MAC) ...
LionHeart: A Layer-based Mapping Framework for Heterogeneous Systems with Analog In-Memory Computing Tiles	2024	arxiv	When arranged in a crossbar configuration, resistive memory devices can be used to execute Matrix-Vector Multiplications (MVMs), the most...
Nonlinear Integrated Microwave Photonics	2013	arxiv	Harnessing nonlinear optical effects in a photonic chip scale has been proven useful for a number of key applications in optical communic...
Crosstalk Reduction for Superconducting Microwave Resonator Arrays	2012	arxiv	Large-scale arrays of Microwave Kinetic Inductance Detectors (MKIDs) are attractive candidates for use in imaging instruments for next ge...
Near-Field Microwave Microscopy of Materials Properties	2000	arxiv	Near-field microwave microscopy has created the opportunity for a new class of

Title	Year	Source	Note
			electrodynamics experiments of materials. Freed from the c...
Bell-state measurement and quantum teleportation using linear optics: two-photon pairs, entangled coherent states, and hybrid entanglement	2013	arxiv	We review and compare Bell-state measurement and quantum teleportation schemes using linear optics with three different types of resource...
Enabling Scalable Photonic Tensor Cores with Polarization-Domain Photonic Computing	2025	arxiv	We present a silicon-photonic tensor core using 2D ferroelectric materials to enable wavelength- and polarization-domain computing. Resul...
Highly-coherent stimulated phonon oscillations in a multi-core optical fiber	2018	arxiv	Opto-mechanical oscillators that generate coherent acoustic waves are drawing much interest, in both fundamental research and application...
The COHERENT Experiment at the Spallation Neutron Source	2015	arxiv	The COHERENT collaboration's primary objective is to measure coherent elastic neutrino-nucleus scattering (CEvNS) using the unique, high-...
CORE -- a COmpact detectoR for the EIC	2022	arxiv	The COmpact detectoR for the Eic (CORE) Proposal was submitted to the EIC "Call for Collaboration Proposals for Detectors". CORE comprehe...
COHERENT Collaboration data release from the first detection of coherent elastic neutrino-nucleus scattering on argon	2020	arxiv	Release of COHERENT collaboration data from the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) on argon. This re...
An optical fiber-based probe for photonic crystal microcavities	2004	arxiv	We review a novel method for characterizing both the spectral and spatial properties of

Title	Year	Source	Note
			resonant cavities within two-dimensional photonic...
[Photovoltaic-ferroelectric materials for the realization of all-optical devices]()	2022	arxiv	Following how the electrical transistor revolutionized the field of electronics,the realization of an optical transistor in which the flo...
[Frequency Ratio Measurements with 18-digit Accuracy Using a Network of Optical Clocks]()	2020	arxiv	Atomic clocks occupy a unique position in measurement science, exhibiting higher accuracy than any other measurement standard and underpi...
[A Fast, robust algorithm for power line interference cancellation in neural recording]()	2014	arxiv	Power line interference may severely corrupt neural recordings at 50/60 Hz and harmonic frequencies. In this paper, we present a robust a...
[Understanding and mitigating noise in trained deep neural networks]()	2021	arxiv	Deep neural networks unlocked a vast range of new applications by solving tasks of which many were previously deemed as reserved to highe...
[Denoising Noisy Neural Networks: A Bayesian Approach with Compensation]()	2021	arxiv	Deep neural networks (DNNs) with noisy weights, which we refer to as noisy neural networks (NoisyNNs), arise from the training and infere...
[Noise and Bell's inequality]()	2010	arxiv	From the beginning of quantum mechanics, there has been a discussion about the concept of reality, as exemplified by the EPR paradox. To ...
[Quantum and Classical Frontiers of Noise]()	2016	arxiv	This paper is an introduction to the eleven works of the special

Title	Year	Source	Note
			issue on Quantum and Classical Frontiers of Noise. The weather, and its ...
Noise based logic: why noise? A comparative study of the necessity of randomness out of orthogonality	2012	arxiv	Although noise-based logic shows potential advantages of reduced power dissipation and the ability of large parallel operations with low ...
Decoherence and noise in open quantum system dynamics	2016	arxiv	We consider the description of quantum noise within the framework of the standard Copenhagen interpretation of quantum mechanics applied ...
Instantaneous noise-based logic	2010	arxiv	We show two universal, Boolean, deterministic logic schemes based on binary noise timefunctions that can be realized without time-averagi...
Noise Dynamics in the Quantum Regime	2023	arxiv	A time-dependent bias voltage on a tunnel junction generates a time-dependent modulation of its current fluctuations, and in particular o...
Simple Cracking of (Noise-Based) Dynamic Watermarking in Smart Grids	2024	arxiv	Previous research employing a conceptual approach with a digital twin has demonstrated that (noise-based) dynamic watermarking is incapab...
Phase-Locked, Low-Noise, Frequency Agile Titanium: Sapphire Lasers for Simultaneous Atom Interferometers	2005	arxiv	We demonstrate phase lock of two >1.6W Titanium:sapphire lasers with a phase noise of -138dBc/Hz at 1MHz from the carrier, using an intra...
Stokes' Drift and Hypersensitive Response with Dichotomous Markov	2005	arxiv	Stochastic Stokes' drift and hypersensitive transport driven

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Noise			by dichotomous noise are theoretically investigated. Explicit mathematical e...
Shot noise for entangled and spin-polarized electrons	2002	arxiv	We review our recent contributions on shot noise for entangled electrons and spin-polarized currents in novel mesoscopic geometries. We f...
The Data Conversion Bottleneck in Analog Computing Accelerators	2023	arxiv	Most modern computing tasks have digital electronic input and output data. Due to these constraints imposed by real-world use cases of co...
Analysis of Performance of Linear Analog Codes	2015	arxiv	In this paper we carefully study the MSE performance of the linear analog codes. We have derived a lower bound of the MSE performance und...
Security of quantum key distribution with detection-efficiency mismatch in the single-photon case: Tight bounds	2018	arxiv	One of the challenges in practical quantum key distribution is dealing with efficiency mismatch between different threshold single-photon...
Performance Analysis of the Matrix Pair Beamformer with Matrix Mismatch	2010	arxiv	Matrix pair beamformer (MPB) is a blind beamformer. It exploits the temporal structure of the signal of interest (SOI) and applies genera...
The three and a half layers of dynamics : analog, digital, semi-digital, analog	2011	arxiv	Quantum theory is extremely successful in explaining most physical phenomena, and is not contradicted by any experiment. Yet, the theory ...

Title	Year	Source	Note
Are Bohmian trajectories real? On the dynamical mismatch between de Broglie-Bohm and classical dynamics in semiclassical systems	2006	arxiv	The de Broglie-Bohm interpretation of quantum mechanics aims to give a realist description of quantum phenomena in terms of the motion of...
Computation over Mismatched Channels	2012	arxiv	We consider the problem of distributed computation of a target function over a multiple-access channel. If the target and channel functio...
Superfluid Analog of the Davies-Unruh Effect	2005	arxiv	We produce an analog of the Davies-Unruh effect for superfluid helium four. There are two temperatures which result--one is associated wi...
Semantic Communications with Discrete-time Analog Transmission: A PAPR Perspective	2022	arxiv	Recent progress in deep learning (DL)-based joint source-channel coding (DeepJSCC) has led to a new paradigm of semantic communications. ...
Programmable photonic circuits	2020	bib	Overview of programmable photonic circuits and phase-control techniques
Coupled oscillators for computing: A review and perspective	2020	bib	Review of coupled oscillator computing mechanisms and synchronization limits
Parallel convolutional processing using an integrated photonic tensor core	2021	bib	Integrated photonic tensor core executing convolutions with phase-change material weights
Oscillatory neurocomputers with dynamic connectivity	1999	bib	Oscillatory neurocomputer concept with dynamic connectivity

Title	Year	Source	Note
A 65nm 4.7TOPS/W 8bit convolutional neural network processor with mixed-signal domain-Specific computing	2018	bib	Mixed-signal CNN accelerator with analog MAC arrays and on-chip calibration
All-optical machine learning using diffractive deep neural networks	2018	bib	Diffractive optical layers performing inference with passive phase masks
Noise mitigation in analog in-memory computing for deep neural network accelerators	2021	bib	Noise-mitigation strategies for analog in-memory neural accelerators
Experimental demonstration of reservoir computing on a silicon photonics chip	2014	bib	Silicon photonic reservoir computing with phase-sensitive interference
Broadcast and weight: An integrated network for scalable photonic spike processing	2014	bib	Frequency-division photonic weighting and coherent summation for neuromorphic spikes
Optimal design for universal multiport interferometers	2016	bib	Compact mesh design for programmable interferometric matrices
Memory devices and applications for in-memory computing	2020	bib	Survey of memory devices for analog in-memory computing and variability mitigation
Deep learning with coherent nanophotonic circuits	2017	bib	Phase-programmable silicon photonic interferometer for matrix multiplication
Neuromorphic photonic networks using silicon photonic weight banks	2017	bib	Silicon photonic weight banks enabling coherent weighted summation
An oscillator-based Ising machine	2019	bib	Oscillator-based Ising machine using spin-torque devices and programmable couplings
Deep physical neural networks trained with backpropagation	2022	bib	Backpropagation through physical systems via hardware-

Title	Year	Source	Note
			in-the-loop calibration

Toy MAC MSE vs SNR

Toy MAC MSE vs SNR

Digits accuracy vs phase noise

Digits accuracy vs phase noise