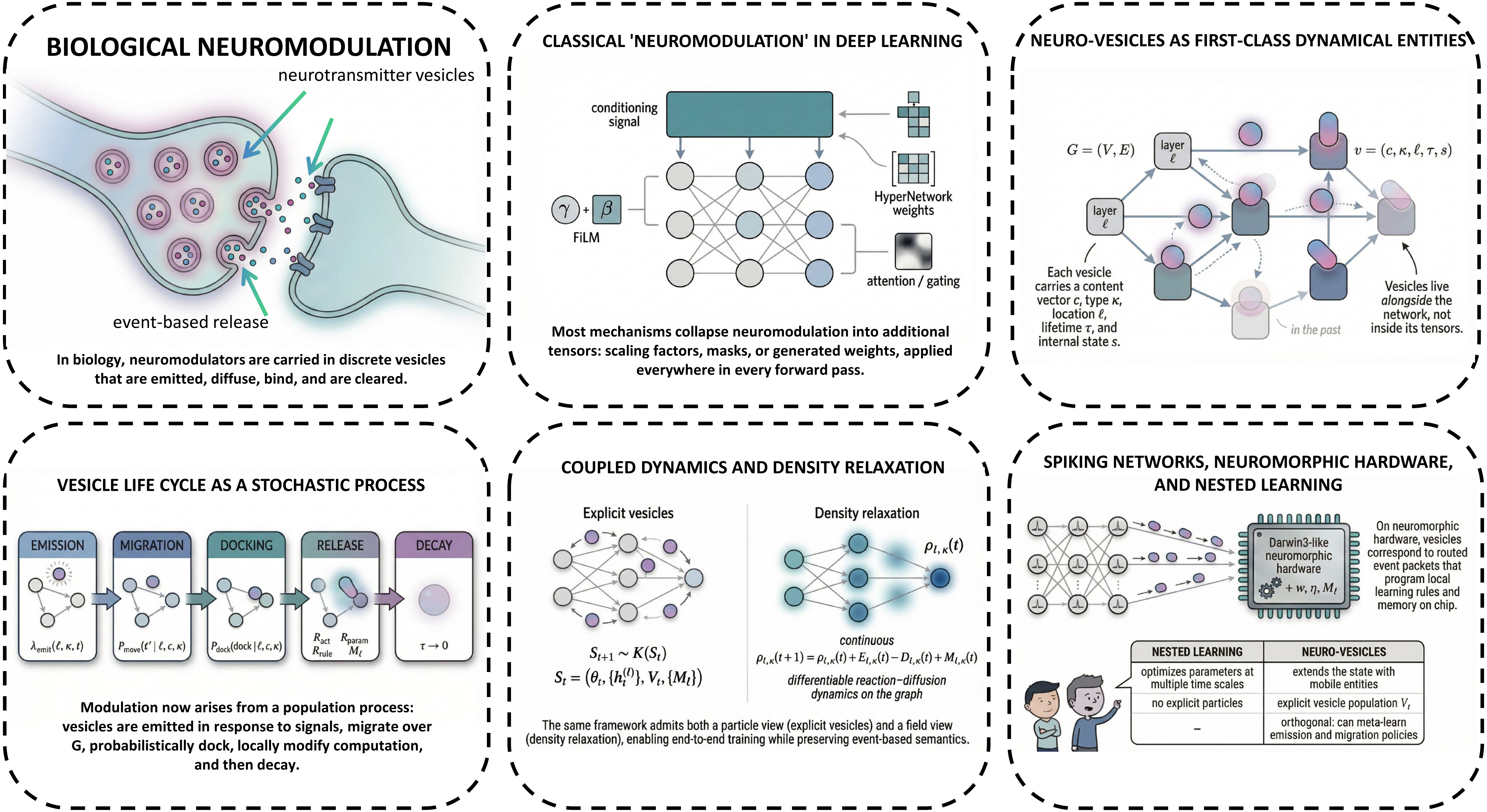
BIOLOGICAL NEUROMODULATION
neurotransmitter vesicles
event-based release
In biology, neuromodulators are carried in discrete vesicles that are emitted, diffuse, bind, and are cleared.
CLASSICAL 'NEUROMODULATION' IN DEEP LEARNING
conditioning signal
γ + β
FiLM
HyperNetwork weights
attention / gating
Most mechanisms collapse neuromodulation into additional tensors: scaling factors, masks, or generated weights, applied everywhere in every forward pass.
NEURO-VESICLES AS FIRST-CLASS DYNAMICAL ENTITIES
$G = (V, E)$
layer ℓ
layer ℓ
$v = (c, \kappa, \ell, \tau, s)$
Each vesicle carries a content vector c, type κ, location ℓ, lifetime τ, and internal state s.
in the past
Vesicles live *alongside* the network, not inside its tensors.
VESICLE LIFE CYCLE AS A STOCHASTIC PROCESS
EMISSION
MIGRATION
DOCKING
RELEASE
DECAY
$\lambda_{\mathrm{emit}}(\ell, \kappa, t)$
$P_{\mathrm{move}}(\ell' \mid \ell, c, \kappa)$
$P_{\mathrm{dock}}(\mathrm{dock} \mid \ell, c, \kappa)$
R_{act} R_{param} R_{rule} M_ℓ
$\tau \to 0$
Modulation now arises from a population process: vesicles are emitted in response to signals, migrate over G, probabilistically dock, locally modify computation, and then decay.
COUPLED DYNAMICS AND DENSITY RELAXATION
Explicit vesicles
$S_{t+1} \sim K(S_t)$
$S_t = \left(\theta_t, \{h_t^{(l)}\}, V_t, \{M_l\}\right)$
Density relaxation
$\rho_{l,\kappa}(t)$
continuous
$\rho_{l,\kappa}(t+1) = \rho_{l,\kappa}(t) + E_{l,\kappa}(t) - D_{l,\kappa}(t) + M_{l,\kappa}(t)$
differentiable reaction–diffusion dynamics on the graph
The same framework admits both a particle view (explicit vesicles) and a field view (density relaxation), enabling end-to-end training while preserving event-based semantics.
SPIKING NETWORKS, NEUROMORPHIC HARDWARE, AND NESTED LEARNING
Darwin3-like neuromorphic hardware
$+ w, \eta, M_\ell$
On neuromorphic hardware, vesicles correspond to routed event packets that program local learning rules and memory on chip.
NESTED LEARNING
NEURO-VESICLES
optimizes parameters at multiple time scales
extends the state with mobile entities
no explicit particles
explicit vesicle population V_t
–
orthogonal: can meta-learn emission and migration policies