

$$\begin{aligned}
L &:= L(z(t), t, \theta) \\
\dot{z}^\alpha(t) &=: f^\alpha(z(t), t, \theta) \\
\Rightarrow z^\alpha(t + \epsilon) &= z^\alpha(t) + \epsilon f^\alpha(z(t), t, \theta) \\
\Rightarrow \frac{\partial z^\beta(t + \epsilon)}{\partial z^\alpha(t)} &= \delta_\alpha^\beta + \epsilon \frac{\partial f^\beta}{\partial z^\alpha(t)}(z(t), t, \theta) \\
a_\alpha(t) &:= \frac{\partial L}{\partial z^\alpha(t)} \\
\frac{\partial L}{\partial z^\alpha(t)} &= \frac{\partial L}{\partial z^\beta(t + \epsilon)} \frac{\partial z^\beta(t + \epsilon)}{\partial z^\alpha(t)} \\
\Rightarrow a_\alpha(t) &= a_\beta(t + \epsilon) \frac{\partial z^\beta(t + \epsilon)}{\partial z^\alpha(t)} = [a_\beta(t) + \epsilon \dot{a}_\beta(t)] \left[\delta_\alpha^\beta + \epsilon \frac{\partial f^\beta}{\partial z^\alpha(t)}(z(t), t, \theta) \right] \\
\Rightarrow \dot{a}_\alpha(t) &= -a_\beta(t) \frac{\partial f^\beta}{\partial z^\alpha(t)}(z(t), t, \theta)
\end{aligned}$$

1 Calculation of $\partial L / \partial \theta$

Suppose the model is layerized, the loss depends on the variables (inputs and model parameters) on the i th layer can be regarded as the loss of a **new** model by truncating the original at the i th layer, which we call $L_i(z_i)$. Varing θ will vary the $L_0(z_0)$ from two aspects, the effect from $dL_1/d\theta$ and the Δz_1 caused by $\Delta\theta$.

$$\frac{dL_0}{d\theta}(z_0) = \frac{dL_1}{d\theta}(z_1) + \frac{dL_1}{dz_1} \frac{\partial z_1}{\partial \theta}.$$

The same relation holds for any i , by simply considering a truncated model,

$$\frac{dL_i}{d\theta}(z_0) = \frac{dL_{i+1}}{d\theta}(z_{i+1}) + \frac{dL_{i+1}}{dz_{i+1}} \frac{\partial z_{i+1}}{\partial \theta}.$$

Thus we have, recursively,

$$\begin{aligned}
\frac{dL_0}{d\theta}(z_0) &= \frac{dL_1}{d\theta}(z_1) + \frac{dL_1}{dz_1} \frac{\partial z_1}{\partial \theta} \\
&= \left[\frac{dL_2}{d\theta}(z_1) + \frac{dL_2}{dz_2} \frac{\partial z_2}{\partial \theta} \right] + \frac{dL_1}{dz_1} \frac{\partial z_1}{\partial \theta} \\
&= \frac{dL_2}{d\theta}(z_1) + \frac{dL_2}{dz_2} \frac{\partial z_2}{\partial \theta} + \frac{dL_1}{dz_1} \frac{\partial z_1}{\partial \theta} \\
&= \dots \\
&= \frac{dL_N}{d\theta}(z_1) + \sum_{i=1}^N \frac{dL_i}{dz_i} \frac{\partial z_i}{\partial \theta}.
\end{aligned}$$

By $z_{i+1}(t) = z_i(t) + \epsilon f(z_i(t), t; \theta)$, $\partial z_i / \partial \theta = \epsilon \partial f(z_i, t; \theta) / \partial \theta$

1 Continuum of Hopfield

1.1 Hopfield Network

Consider Hopfield network. Let $x(t) \in \{-1, +1\}^N$ denotes the state of the network at discrete time $t = 0, 1, \dots$; and W a matrix on \mathbb{R}^N , essentially ensuring $W_{\alpha\beta} = W_{\beta\alpha}$ and $W_{\alpha\alpha} = 0$. Define energy $E_W(x(t)) := -W_{\alpha\beta} x^\alpha(t) x^\beta(t)$.

Theorem 1. Along dynamics $x_\alpha(t+1) = \text{sign}[W_{\alpha\beta} x^\beta(t)]$, $E_W(x(t+1)) - E_W(x(t)) \leq 0$.

Proof. Consider the async-updation of Hopfield network. Let's change the component at dimension $\hat{\alpha}$, i.e. $x'_{\hat{\alpha}} = \text{sign}[W_{\hat{\alpha}\beta} x^\beta]$, then

$$\begin{aligned}
E_W(x') - E_W(x) &= -W_{\alpha\beta} x'^\alpha x'^\beta + W_{\alpha\beta} x^\alpha x^\beta \\
&= -2(x'^{\hat{\alpha}} - x^{\hat{\alpha}}) W_{\hat{\alpha}\beta} x^\beta,
\end{aligned}$$

which employs conditions $W_{\alpha\beta} = W_{\beta\alpha}$ and $W_{\alpha\alpha} = 0$. Next, we prove that, combining with $x'_{\hat{\alpha}} = \text{sign}[W_{\hat{\alpha}\beta}x^{\beta}]$, this implies $E_W(x') - E_W(x) \leq 0$.

If $(x'^{\hat{\alpha}} - x^{\hat{\alpha}}) > 0$, then $x'^{\hat{\alpha}} = 1$ and $x^{\hat{\alpha}} = -1$. Since $x'_{\hat{\alpha}} = \text{sign}[W_{\hat{\alpha}\beta}x^{\beta}]$, $W_{\hat{\alpha}\beta}x^{\beta} > 0$. Then $E_W(x') - E_W(x) < 0$. Contrarily, if $(x'^{\hat{\alpha}} - x^{\hat{\alpha}}) < 0$, then $x'^{\hat{\alpha}} = -1$ and $x^{\hat{\alpha}} = 1$, implying $W_{\hat{\alpha}\beta}x^{\beta} < 0$. Also $E_W(x') - E_W(x) < 0$. Otherwise, $E_W(x') - E_W(x) = 0$. So, we conclude $E_W(x') - E_W(x) \leq 0$. \square

Since the states of the network are finite, the E_W is lower bounded. Thus the network converges (relaxes) at finite t .

1.2 Continuum

Let's consider applying the convergence of Hopfield network to neural ODE for generic network architecture. This makes the discrete time t a continuum.

Theorem 2. *Let M be a Riemann manifold with metric g . Given any function $\mathcal{E} \in C^1(M, \mathbb{R})$. Let $x(t) \in C^1(\mathbb{R}, M)$ denote trajectory. Then, $d\mathcal{E}/dt \leq 0$ along $x(t)$ if*

$$\frac{dx^{\alpha}}{dt}(t) = -\nabla^{\alpha}\mathcal{E}(x(t)).$$

Proof. We have

$$\frac{d\mathcal{E}}{dt}(t) = \nabla_{\alpha}\mathcal{E}(x(t))\frac{dx^{\alpha}}{dt}(t) = -\nabla_{\alpha}\mathcal{E}(x(t))\nabla^{\alpha}\mathcal{E}(x(t)) \leq 0. \quad \square$$

Further, if the function \mathcal{E} is lower bounded, then the trajectory converges (relaxes) at finite t . We call this dynamic with lower bounded \mathcal{E} as ‘‘Hopfield dynamic with energy \mathcal{E} ’’.

This is the continuum analogy to the convergence of Hopfield network. Indeed, let M be \mathbb{R}^N , and $\mathcal{E}(x) = -W_{\alpha\beta}x^{\alpha}x^{\beta}$ with $W_{\alpha\beta} = W_{\beta\alpha}$, then dynamics becomes

$$\frac{dx^{\alpha}}{dt}(t) = -\nabla_{\alpha}\mathcal{E}(x(t)) = -2W_{\alpha\beta}x^{\beta}(t),$$

which makes

$$\frac{d\mathcal{E}}{dt}(t) = -2\frac{dx^{\alpha}}{dt}(t)W_{\alpha\beta}x^{\beta}(t).$$

Comparing with the proof of convergence of Hopfield network, i.e. $\Delta E_W(x) = -2\Delta x^{\alpha}W_{\alpha\beta}x^{\beta}$, the analogy is obvious. The only differences are that the condition $W_{\alpha\alpha} = 0$ and the sign-function are absent here.

It is known that a Riemann manifold can be locally re-coordinated to be Euclidean. Thus, locally $\exists \hat{x}$ coordinate, s.t.

$$\frac{dx^{\alpha}}{dt}(t) = -\delta^{\alpha\beta}\frac{\partial\mathcal{E}}{\partial x^{\beta}}(x(t)).$$