Gated Recurrent Unit (GRU): back-propagation derivation

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Abstract

This document contains derivation of the gradients for a Gated Recurrent Unit (a type of RNN-block) using back-propagation (or reverse-mode differentiation). For the implementation of the neural-network see the accompanying notebooks.

1 Block Architecture

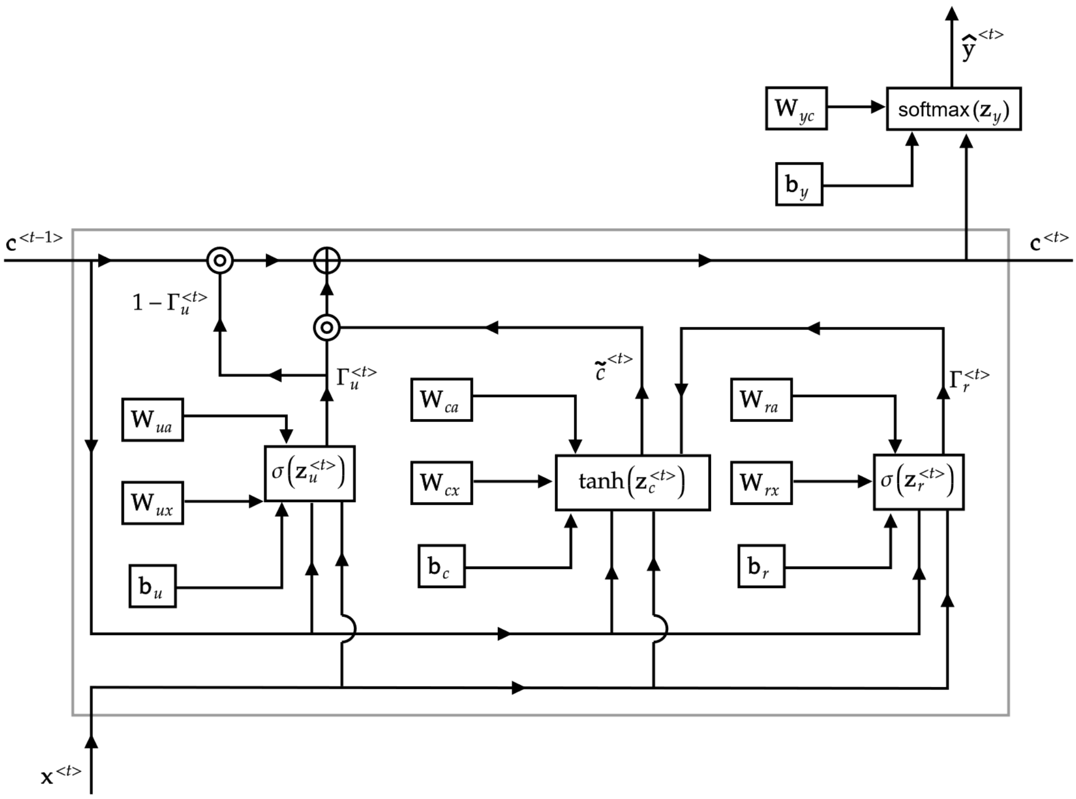

Figure 1: forward propagation diagram for a GRU-block at time-step t. The concentric circles represent a hadamard-product (i.e. $\mathbf{x} \circ \mathbf{y}$) of the input vectors.

2 Forward Propagation

Given, $\mathbf{c}^{\langle t-1\rangle}$ from the $(t-1)^{th}$ time-step, the equations for forward propagation through the t^{th} time-step, are as follows: (see figure-1)

$$\begin{aligned}
\mathbf{z}_u^{\langle t\rangle} &= \mathbf{W}_{uc}^{\intercal}\,\mathbf{c}^{\langle t-1\rangle} + \mathbf{W}_{ux}^{\intercal}\,\mathbf{x}^{\langle t\rangle} + \mathbf{b}_u && \text{eq.1}\\
\Gamma_u^{\langle t\rangle} &= \sigma(\mathbf{z}_u^{\langle t\rangle}) && \text{eq.2}\\
\mathbf{z}_r^{\langle t\rangle} &= \mathbf{W}_{rc}^{\intercal}\,\mathbf{c}^{\langle t-1\rangle} + \mathbf{W}_{rx}^{\intercal}\,\mathbf{x}^{\langle t\rangle} + \mathbf{b}_r && \text{eq.3}\\
\Gamma_r^{\langle t\rangle} &= \sigma(\mathbf{z}_r^{\langle t\rangle}) && \text{eq.4}\\
\mathbf{z}_c^{\langle t\rangle} &= \mathbf{W}_{cc}^{\intercal}\,\left(\Gamma_r^{\langle t\rangle} \circ \mathbf{c}^{\langle t-1\rangle}\right) + \mathbf{W}_{cx}^{\intercal}\,\mathbf{x}^{\langle t\rangle} + \mathbf{b}_c && \text{eq.5}\\
\tilde{\mathbf{c}}^{\langle t\rangle} &= \tanh(\mathbf{z}_c^{\langle t\rangle}) && \text{eq.6}\\
\mathbf{c}^{\langle t\rangle} &= \Gamma_u^{\langle t\rangle} \circ \tilde{\mathbf{c}}^{\langle t\rangle} + (1-\Gamma_u^{\langle t\rangle}) \circ \mathbf{c}^{\langle t-1\rangle} && \text{eq.7}\\
\mathbf{z}_y^{\langle t\rangle} &= \mathbf{W}_{ya}^{\intercal}\,\mathbf{c}^{\langle t\rangle} + \mathbf{b}_y && \text{eq.8}\\
\hat{\mathbf{y}}^{\langle t\rangle} &= \text{softmax}\left(\mathbf{z}_y^{\langle t\rangle}\right) && \text{eq.9}
\end{aligned}$$

where,

$$\begin{aligned}
\mathbf{x}^{\langle t\rangle} &\text{ is a } (n_x, 1)\text{-dimensional vector}\\
\mathbf{c}^{\langle t\rangle} \,\&\, \mathbf{c}^{\langle t-1\rangle} \,\&\, \tilde{\mathbf{c}}^{\langle t\rangle} &\text{ are } (n_a, 1)\text{-dimensional vectors}\\
\mathbf{W}_{*c}, * \in \{r, u, c\} &\text{ are } (n_a, n_a)\text{-dimensional parameter matrices}\\
\mathbf{W}_{*x}, * \in \{r, u, c\} &\text{ are } (n_x, n_a)\text{-dimensional parameter matrices}\\
\mathbf{b}_{*}, * \in \{r, u, c\} &\text{ are } (n_a, 1)\text{-dimensional bias-vectors}\\
\Gamma_*^{\langle t\rangle}, * \in \{r, u\} &\text{ are } (n_a, 1)\text{-dimensional vector, which represents a gate}\\
\mathbf{z}_*^{\langle t\rangle}, * \in \{r, u, c\} &\text{ are } (n_a, 1)\text{-dimensional vector, is input to a gates' activation}\\
\mathbf{W}_{yc} &\text{ is a } (n_a, n_y)\text{-dimensional parameter matrix}\\
\mathbf{b}_y &\text{ is a } (n_y, 1)\text{-dimensional bias vector}
\end{aligned}$$

Also, the sub-scripts denote the following: $_r$ - relevance-gate, and $_u$ - update-gate.

3 Backward Propagation

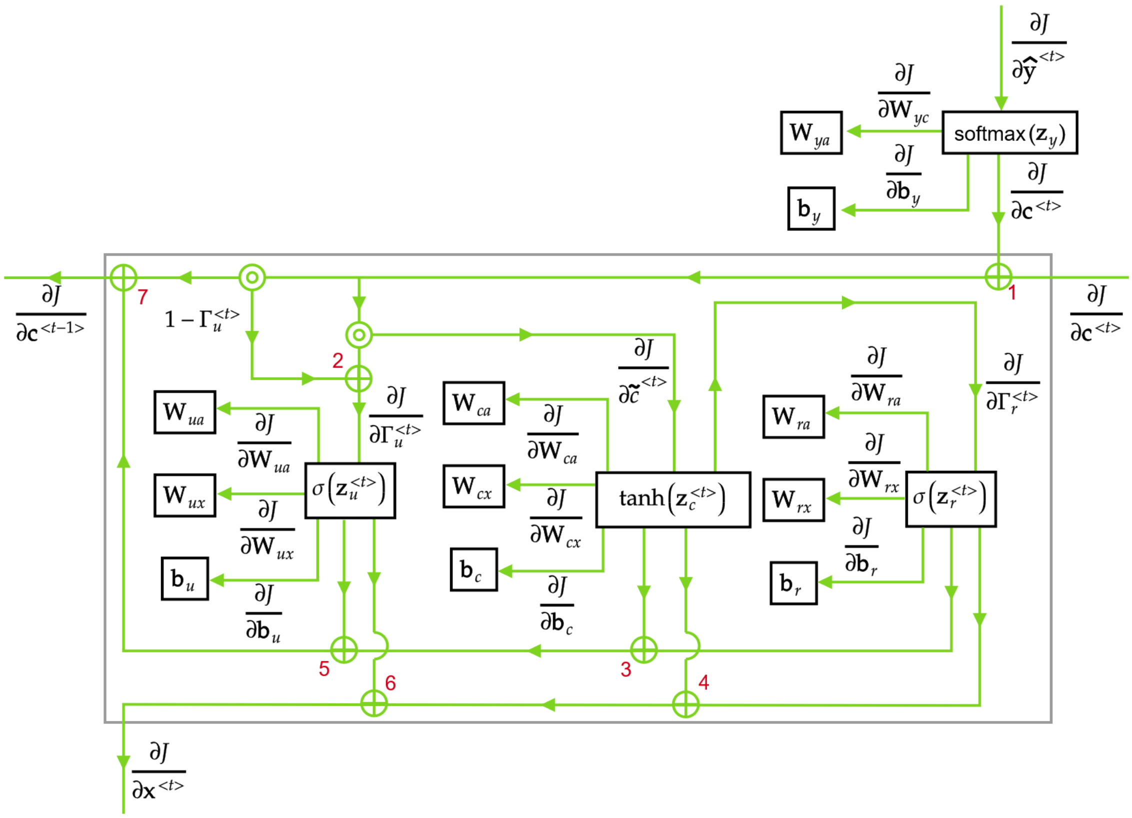

Figure 2: backward-propagation/gradient-flow diagram for a LSTM-block at time-step t. The concentric circles represent a hadamard-product (i.e. $\mathbf{x} \circ \mathbf{y}$) of the input vectors.

3.1 Computing $\frac{\partial J}{\partial \hat{\mathbf{y}}^{\langle t \rangle}}$

Since, $\hat{\mathbf{y}}^{\langle t \rangle}$ is computed using the softmax() activation-function, the loss J is computed using the cross-entropy loss. Also, let $\mathbf{y}^{\langle t \rangle}$ be the output-label corresponding to the t^{th} time-step. Then,

$$\begin{aligned}
\frac{\partial J}{\partial \hat{\mathbf{y}}^{\langle t \rangle}} &= \begin{bmatrix} \frac{\partial J}{\partial \hat{y}_1^{\langle t \rangle}} & \frac{\partial J}{\partial \hat{y}_2^{\langle t \rangle}} & \cdots & \frac{\partial J}{\partial \hat{y}_{n_y}^{\langle t \rangle}} \end{bmatrix} \\
&= \begin{bmatrix} \frac{y_1^{\langle t \rangle}}{\hat{y}_1^{\langle t \rangle}} & \frac{y_2^{\langle t \rangle}}{\hat{y}_2^{\langle t \rangle}} & \cdots & \frac{y_{n_y}^{\langle t \rangle}}{\hat{y}_{n_y}^{\langle t \rangle}} \end{bmatrix}
\end{aligned}$$

3.2 Computing $\frac{\partial J}{\partial \mathbf{W}_{yc}}$ and $\frac{\partial J}{\partial \mathbf{b}_y}$

From *eq.9* (see section-2), we have

$$\begin{aligned}
\frac{\partial J}{\partial \mathbf{z}_y^{\langle t \rangle}} &= \frac{\partial J}{\partial \hat{\mathbf{y}}^{\langle t \rangle}} \frac{\partial \hat{\mathbf{y}}^{\langle t \rangle}}{\partial \mathbf{z}_y^{\langle t \rangle}} \\
&= \frac{\partial J}{\partial \hat{\mathbf{y}}^{\langle t \rangle}} \left(\mathrm{diag}(\hat{\mathbf{y}}^{\langle t \rangle}) - \hat{\mathbf{y}}^{\langle t \rangle}(\hat{\mathbf{y}}^{\langle t \rangle})^{\intercal}\right)
\end{aligned}$$

Note: for more on the derivation of the derivative of a `softmax()` function, see `..\notes\softmax-function.ipynb`

From *eq.8* (see section-2), we have

$$\mathrm{tr}(J) = \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle r\rangle}} \mathrm{d}\mathbf{z}_y^{\langle t\rangle}\right)$$

where, $\mathrm{d}\mathbf{z}_y^{\langle t\rangle}$ can be expanded as follows:

$$\begin{aligned}\mathrm{d}\mathbf{z}_y^{\langle t\rangle} &= \mathrm{d}\left(\mathbf{W}_{yc}^{\intercal}\mathbf{c}^{\langle t\rangle} + \mathbf{b}_y\right)\\ &= \mathrm{d}\left(\mathbf{W}_{yc}^{\intercal}\right)\mathbf{c}^{\langle t\rangle} + \mathbf{W}_{yc}^{\intercal}\mathrm{d}\mathbf{c}^{\langle t\rangle} + \mathrm{d}\mathbf{b}_y \qquad \text{eq.9-1}\end{aligned}$$

when differentiating w.r.t. $\mathbf{W}_{yc}$, we have $\mathrm{d}\mathbf{c}^{\langle t\rangle} = 0$, and $\mathrm{d}\mathbf{b}_y = 0$. So,

$$\begin{aligned}\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{yc}^{\intercal}\mathbf{c}^{\langle t\rangle}\right)\\ &= \mathrm{tr}\left(\left(\mathbf{c}^{\langle t\rangle}\right)^{\intercal}\mathrm{d}\mathbf{W}_{yc}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\right)^{\intercal}\right)\\ &= \mathrm{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{c}^{\langle t\rangle}\right)^{\intercal}\mathrm{d}\mathbf{W}_{yc}\right)\\ \Longrightarrow \frac{\partial J}{\partial \mathbf{W}_{yc}} &= \left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{c}^{\langle t\rangle}\right)^{\intercal}\end{aligned}$$

when differentiating w.r.t. $\mathbf{b}_y$, we have $\mathrm{d}\mathbf{c}^{\langle t\rangle} = 0$, and $\mathrm{d}\mathbf{W}_{yc} = 0$. So,

$$\begin{aligned}\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\,\mathrm{d}\mathbf{b}_y^{\intercal}\right)\\ \Longrightarrow \frac{\partial J}{\partial \mathbf{b}_y} &= \frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\end{aligned}$$

3.3 Computing $\frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}}$

This derivative has two components

Comp-1 flows-in from the $(t+1)^{th}$ time-step, and

Comp-2 flows-in as the derivative from $\hat{\mathbf{y}}^{\langle t\rangle}$. This derivative is computed using *eq.9-1* as follows,

$$\begin{aligned}\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\mathrm{d}\mathbf{z}_y^{\langle t\rangle}\right)\\ &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\mathbf{W}_{yc}^{\intercal}\,\mathrm{d}\mathbf{c}^{\langle t\rangle}\right)\\ \Longrightarrow \frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}} &= \frac{\partial J}{\partial \mathbf{z}_y^{\langle t\rangle}}\mathbf{W}_{yc}^{\intercal}\end{aligned}$$

These two components are added to compute the true derivative (see the $\oplus$ labeled as *1* in the figure-2), i.e.

$$\frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} = \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}}\right|_{\textbf{Comp-1}} + \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}}\right|_{\textbf{Comp-2}}$$

3.4 Computing $\frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t \rangle}}$ and $\frac{\partial J}{\partial \Gamma_u^{\langle t \rangle}}$

From *eq.7* (see section-2), we have

$$\begin{aligned}
\frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t \rangle}} &= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \frac{\partial \mathbf{c}^{\langle t \rangle}}{\partial \tilde{\mathbf{c}}^{\langle t \rangle}} \\
&= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \operatorname{diag}\left(\Gamma_u^{\langle t \rangle}\right) \\
&= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \circ \left(\Gamma_u^{\langle t \rangle}\right)^\intercal
\end{aligned}$$

$$\begin{aligned}
\frac{\partial J}{\partial \Gamma_u^{\langle t \rangle}} &= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \frac{\partial \mathbf{c}^{\langle t \rangle}}{\partial \Gamma_u^{\langle t \rangle}} \\
&= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \operatorname{diag}\left(\tilde{\mathbf{c}}^{\langle t \rangle} - \mathbf{c}^{\langle t-1 \rangle}\right) \\
&= \frac{\partial J}{\partial \mathbf{c}^{\langle t \rangle}} \circ \left(\tilde{\mathbf{c}}^{\langle t \rangle} - \mathbf{c}^{\langle t-1 \rangle}\right)^\intercal
\end{aligned}$$

3.5 Computing $\frac{\partial J}{\partial \mathbf{W}_{cc}}$, $\frac{\partial J}{\partial \mathbf{W}_{cx}}$, and $\frac{\partial J}{\partial \mathbf{b}_c}$

From *eq.6* (see section-2), we have

$$\begin{aligned}
\frac{\partial J}{\partial \mathbf{z}_c^{\langle t \rangle}} &= \frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t \rangle}} \frac{\partial \tilde{\mathbf{c}}^{\langle t \rangle}}{\partial \mathbf{z}_c^{\langle t \rangle}} \\
&= \frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t \rangle}} \circ \left[\mathbf{1}_{(n_a,1)} - \tanh^2(\mathbf{z}_c^{\langle t \rangle})\right]^\intercal
\end{aligned}$$

From *eq.5* (see section-2), using the trace-method, we have

$$\operatorname{tr}(J) = \operatorname{tr}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t \rangle}} \, \mathrm{d}\mathbf{z}_c^{\langle t \rangle}\right)$$

where, $\mathrm{d}\mathbf{z}_c^{\langle t \rangle}$ can be expanded as follows:

$$\begin{aligned}
\mathrm{d}\mathbf{z}_c^{\langle t \rangle} &= \mathrm{d}\left(\mathbf{W}_{cc}^\intercal \left(\Gamma_r^{\langle t \rangle} \circ \mathbf{c}^{\langle t-1 \rangle}\right) + \mathbf{W}_{cx}^\intercal \mathbf{x}^{\langle t \rangle} + \mathbf{b}_c\right) \\
&= \mathrm{d}\mathbf{W}_{cc}^\intercal \left(\Gamma_r^{\langle t \rangle} \circ \mathbf{c}^{\langle t-1 \rangle}\right) + \mathbf{W}_{cc}^\intercal \, \mathrm{d}\left(\Gamma_r^{\langle t \rangle} \circ \mathbf{c}^{\langle t-1 \rangle}\right) + \mathrm{d}\mathbf{W}_{cx}^\intercal \mathbf{x}^{\langle t \rangle} \\
&\quad + \mathbf{W}_{cx}^\intercal \, \mathrm{d}\mathbf{x}^{\langle t \rangle} + \mathrm{d}\mathbf{b}_c \qquad \text{eq.9-2}
\end{aligned}$$

when differentiating w.r.t. $\mathbf{W}_{cc}$, we have $\mathrm{d}\mathbf{W}_{cx} = 0$, $\mathrm{d}\left(\Gamma_r^{\langle t \rangle} \circ \mathbf{c}^{\langle t-1 \rangle}\right) = 0$, $\mathrm{d}\mathbf{b}_c = 0$, and $\mathrm{d}\mathbf{x}^{\langle t \rangle} = 0$. So,

$$
\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{cc}^{\intercal}\,\left(\Gamma_r^{\langle t\rangle}\circ \mathbf{c}^{\langle t-1\rangle}\right)\right)\\
&= \mathrm{tr}\left(\left(\Gamma_r^{\langle t\rangle}\circ \mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{cc}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\right)\\
&= \mathrm{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\left(\Gamma_r^{\langle t\rangle}\circ \mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{cc}\right)\\
\Longrightarrow \frac{\partial J}{\partial \mathbf{W}_{cc}} &= \left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\left(\Gamma_r^{\langle t\rangle}\circ \mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}
\end{aligned}
$$

when differentiating w.r.t. $\mathbf{W}_{cx}$, we have $\mathrm{d}\mathbf{W}_{cc}=0$, $\mathrm{d}\left(\Gamma_r^{\langle t\rangle}\circ \mathbf{c}^{\langle t-1\rangle}\right)=0$, $\mathrm{d}\mathbf{b}_c=0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle}=0$. So,

$$
\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{cx}^{\intercal}\,\mathbf{x}^{\langle t\rangle}\right)\\
&= \mathrm{tr}\left(\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{cx}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\right)\\
&= \mathrm{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{cx}\right)\\
\Longrightarrow \frac{\partial J}{\partial \mathbf{W}_{cx}} &= \left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}
\end{aligned}
$$

when differentiating w.r.t. $\mathbf{b}_c$, we have $\mathrm{d}\mathbf{W}_{cc}=0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle}=0$, $\mathrm{d}\mathbf{W}_{cx}=0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle}=0$. So,

$$
\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}\,\mathrm{d}\mathbf{b}_c\right)\\
\Longrightarrow \frac{\partial J}{\partial \mathbf{b}_c} &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}}
\end{aligned}
$$

3.6 Computing $\frac{\partial J}{\partial \mathbf{W}_{uc}}$, $\frac{\partial J}{\partial \mathbf{W}_{ux}}$, and $\frac{\partial J}{\partial \mathbf{b}_u}$

From *eq.2* (see section-2), we have

$$
\begin{aligned}
\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}} &= \frac{\partial J}{\partial \Gamma_u^{\langle t\rangle}}\frac{\partial \Gamma_u^{\langle t\rangle}}{\partial \mathbf{z}_u^{\langle t\rangle}}\\
&= \frac{\partial J}{\partial \Gamma_u^{\langle t\rangle}}\circ\left(\Gamma_u^{\langle t\rangle}\circ\left(\mathbf{1}_{(n_c,1)}-\Gamma_u^{\langle t\rangle}\right)\right)^{\intercal}
\end{aligned}
$$

From *eq.1* (see section-2), using the trace-method, we have

$$
\mathrm{tr}(J) = \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\,\mathrm{d}\mathbf{z}_u^{\langle t\rangle}\right)
$$

where, $\mathrm{d}\mathbf{z}_u^{\langle t\rangle}$ can be expanded as follows:

$$
\begin{aligned}
\mathrm{d}\mathbf{z}_u^{\langle t\rangle} &= \mathrm{d}\left(\mathbf{W}_{uc}^{\intercal}\,\mathbf{c}^{\langle t-1\rangle}+\mathbf{W}_{ux}^{\intercal}\,\mathbf{x}^{\langle t\rangle}+\mathbf{b}_u\right)\\
&= \mathrm{d}\mathbf{W}_{uc}^{\intercal}\,\mathbf{c}^{\langle t-1\rangle}+\mathbf{W}_{uc}^{\intercal}\,\mathrm{d}\mathbf{c}^{\langle t-1\rangle}+\mathrm{d}\mathbf{W}_{ux}^{\intercal}\,\mathbf{x}^{\langle t\rangle}+\mathbf{W}_{ux}^{\intercal}\,\mathrm{d}\mathbf{x}^{\langle t\rangle}+\mathrm{d}\mathbf{b}_u \qquad \text{eq.9-2}
\end{aligned}
$$

when differentiating w.r.t. $\mathbf{W}_{uc}$, we have $\mathrm{d}\mathbf{W}_{ux} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{b}_u = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{uc}^{\intercal}\,\mathbf{c}^{\langle t-1\rangle}\right) \\
&= \mathrm{tr}\left(\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{uc}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\right) \\
&= \mathrm{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{uc}\right) \\
\implies \frac{\partial J}{\partial \mathbf{W}_{uc}} &= \left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}
\end{aligned}$$

when differentiating w.r.t. $\mathbf{W}_{ux}$, we have $\mathrm{d}\mathbf{W}_{uc} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{b}_u = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{ux}^{\intercal}\,\mathbf{x}^{\langle t\rangle}\right) \\
&= \mathrm{tr}\left(\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{ux}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\right) \\
&= \mathrm{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}\,\mathrm{d}\mathbf{W}_{ux}\right) \\
\implies \frac{\partial J}{\partial \mathbf{W}_{ux}} &= \left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\right)^{\intercal}\left(\mathbf{x}^{\langle t\rangle}\right)^{\intercal}
\end{aligned}$$

when differentiating w.r.t. $\mathbf{b}_u$, we have $\mathrm{d}\mathbf{W}_{uc} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{W}_{ux} = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}
\mathrm{d}J &= \mathrm{tr}\left(\frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}\,\mathrm{d}\mathbf{b}_u\right) \\
\implies \frac{\partial J}{\partial \mathbf{b}_u} &= \frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}}
\end{aligned}$$

3.7 Computing $\frac{\partial J}{\partial \Gamma_r^{\langle t\rangle}}$

From the results in section-3.5 and, from *eq.9-2*, we have

$$\begin{aligned}
\frac{\partial J}{\partial \Gamma_r^{\langle t\rangle}} &= \frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}\frac{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}{\partial \Gamma_r^{\langle t\rangle}} \\
&= \frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}\frac{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}{\partial\left(\Gamma_r^{\langle t\rangle}\circ\mathbf{c}^{\langle t-1\rangle}\right)}\frac{\partial\left(\Gamma_r^{\langle t\rangle}\circ\mathbf{c}^{\langle t-1\rangle}\right)}{\partial \Gamma_r^{\langle t\rangle}} \\
&= \frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}\mathbf{W}_{cc}^{\intercal}\,\mathrm{diag}\left(\mathbf{c}^{\langle t-1\rangle}\right) \\
&= \left(\frac{\partial J}{\partial \tilde{\mathbf{c}}^{\langle t\rangle}}\mathbf{W}_{cc}^{\intercal}\right)\circ\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\intercal}
\end{aligned}$$

Note: for more information on the derivative of a Hadamard product, see the Appendix-A in `.\backprop-lstm.pdf`.

3.8 Computing $\frac{\partial J}{\partial \mathbf{W}_{rc}}$, $\frac{\partial J}{\partial \mathbf{W}_{rx}}$, and $\frac{\partial J}{\partial \mathbf{b}_r}$

From *eq.4* (see section-2), we have

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}} &= \frac{\partial J}{\partial \Gamma_r^{\langle t\rangle}} \frac{\partial \Gamma_r^{\langle t\rangle}}{\partial \mathbf{z}_r^{\langle t\rangle}} \\ &= \frac{\partial J}{\partial \Gamma_r^{\langle t\rangle}} \circ \left(\Gamma_r^{\langle t\rangle} \circ (\mathbf{1}_{(n_c,1)} - \Gamma_r^{\langle t\rangle})\right)^{\mathsf{T}}\end{aligned}$$

From *eq.3* (see section-2), using the trace-method, we have

$$\operatorname{tr}(J) = \operatorname{tr}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}} \,\mathrm{d}\mathbf{z}_r^{\langle t\rangle}\right)$$

where, $\mathrm{d}\mathbf{z}_r^{\langle t\rangle}$ can be expanded as follows:

$$\begin{aligned}\mathrm{d}\mathbf{z}_r^{\langle t\rangle} &= \mathrm{d}\left(\mathbf{W}_{rc}^{\mathsf{T}}\,\mathbf{c}^{\langle t-1\rangle} + \mathbf{W}_{rx}^{\mathsf{T}}\,\mathbf{x}^{\langle t\rangle} + \mathbf{b}_r\right) \\ &= \mathrm{d}\mathbf{W}_{rc}^{\mathsf{T}}\,\mathbf{c}^{\langle t-1\rangle} + \mathbf{W}_{rc}^{\mathsf{T}}\,\mathrm{d}\mathbf{c}^{\langle t-1\rangle} + \mathrm{d}\mathbf{W}_{rx}^{\mathsf{T}}\,\mathbf{x}^{\langle t\rangle} + \mathbf{W}_{rx}^{\mathsf{T}}\,\mathrm{d}\mathbf{x}^{\langle t\rangle} + \mathrm{d}\mathbf{b}_r \qquad \text{eq.9-3}\end{aligned}$$

when differentiating w.r.t. $\mathbf{W}_{rc}$, we have $\mathrm{d}\mathbf{W}_{rx} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{b}_r = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}\mathrm{d}J &= \operatorname{tr}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{rc}^{\mathsf{T}}\,\mathbf{c}^{\langle t-1\rangle}\right) \\ &= \operatorname{tr}\left(\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\mathsf{T}}\,\mathrm{d}\mathbf{W}_{rc}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\right) \\ &= \operatorname{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\mathsf{T}}\,\mathrm{d}\mathbf{W}_{rc}\right) \\ \Longrightarrow \frac{\partial J}{\partial \mathbf{W}_{rc}} &= \left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\left(\mathbf{c}^{\langle t-1\rangle}\right)^{\mathsf{T}}\end{aligned}$$

when differentiating w.r.t. $\mathbf{W}_{rx}$, we have $\mathrm{d}\mathbf{W}_{rc} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{b}_r = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}\mathrm{d}J &= \operatorname{tr}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\,\mathrm{d}\mathbf{W}_{rx}^{\mathsf{T}}\,\mathbf{x}^{\langle t\rangle}\right) \\ &= \operatorname{tr}\left(\left(\mathbf{x}^{\langle t\rangle}\right)^{\mathsf{T}}\,\mathrm{d}\mathbf{W}_{rx}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\right) \\ &= \operatorname{tr}\left(\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\left(\mathbf{x}^{\langle t\rangle}\right)^{\mathsf{T}}\,\mathrm{d}\mathbf{W}_{rx}\right) \\ \Longrightarrow \frac{\partial J}{\partial \mathbf{W}_{rx}} &= \left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\right)^{\mathsf{T}}\left(\mathbf{x}^{\langle t\rangle}\right)^{\mathsf{T}}\end{aligned}$$

when differentiating w.r.t. $\mathbf{b}_r$, we have $\mathrm{d}\mathbf{W}_{rc} = 0$, $\mathrm{d}\mathbf{c}^{\langle t-1\rangle} = 0$, $\mathrm{d}\mathbf{W}_{rx} = 0$, and $\mathrm{d}\mathbf{x}^{\langle t\rangle} = 0$. So,

$$\begin{aligned}\mathrm{d}J &= \operatorname{tr}\left(\frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\,\mathrm{d}\mathbf{b}_r\right) \\ \Longrightarrow \frac{\partial J}{\partial \mathbf{b}_r} &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}}\end{aligned}$$

3.9 Computing $\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}$, and $\frac{\partial J}{\partial \mathbf{x}^{\langle t\rangle}}$

The derivative $\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}$ has four components, as follows

Comp-1 flows-in as part of the derivative $\frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}}$. This derivative is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}} &= \frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}} \frac{\partial \mathbf{c}^{\langle t\rangle}}{\partial \mathbf{c}^{\langle t-1\rangle}} \\ &= \frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}} \operatorname{diag}\left(\mathbf{1}_{(n_c,1)} - \Gamma_u^{\langle t\rangle}\right) \\ &= \frac{\partial J}{\partial \mathbf{c}^{\langle t\rangle}} \circ \left(\mathbf{1}_{(n_c,1)} - \Gamma_u^{\langle t\rangle}\right)^{\intercal}\end{aligned}$$

Comp-2 flows-in as derivative from $\Gamma_r^{\langle t\rangle}$ (see *eq.9-3*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}} &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}} \frac{\partial \mathbf{z}_r^{\langle t\rangle}}{\partial \mathbf{c}^{\langle t-1\rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}} \mathbf{W}_{rc}^{\intercal}\end{aligned}$$

Comp-3 flows-in as derivative from $\Gamma_u^{\langle t\rangle}$ (see *eq.9-2*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}} &= \frac{\partial J}{\partial \mathbf{z}_u^{\langle t\rangle}} \frac{\partial \mathbf{z}_u^{\langle t\rangle}}{\partial \mathbf{c}^{\langle t-1\rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t\rangle}} \mathbf{W}_{uc}^{\intercal}\end{aligned}$$

Comp-4 flows-in as derivative from $\tilde{\mathbf{c}}^{\langle t\rangle}$ (see *eq.9-2*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}} &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}} \frac{\partial \mathbf{z}_c^{\langle t\rangle}}{\partial \mathbf{c}^{\langle t-1\rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}} \frac{\partial \mathbf{z}_c^{\langle t\rangle}}{\partial \left(\Gamma_r^{\langle t\rangle} \circ \mathbf{c}^{\langle t-1\rangle}\right)} \frac{\partial \left(\Gamma_r^{\langle t\rangle} \circ \mathbf{c}^{\langle t-1\rangle}\right)}{\partial \mathbf{c}^{\langle t-1\rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}} \mathbf{W}_{cc}^{\intercal} \operatorname{diag}\left(\Gamma_r^{\langle t\rangle}\right) \\ &= \left(\frac{\partial J}{\partial \mathbf{z}_c^{\langle t\rangle}} \mathbf{W}_{cc}^{\intercal}\right) \circ \left(\Gamma_r^{\langle t\rangle}\right)^{\intercal}\end{aligned}$$

These four components are then added to compute the true derivative, i.e.

$$\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}} = \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}\right|_{\textbf{Comp-1}} + \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}\right|_{\textbf{Comp-2}} + \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}\right|_{\textbf{Comp-3}} + \left.\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}\right|_{\textbf{Comp-4}}$$

(see $\oplus$ labeled as *3*, *5*, and *7* in figure-2)

The derivative $\frac{\partial J}{\partial \mathbf{c}^{\langle t-1\rangle}}$ has three components, as follows

Comp-1 flows-in as derivative from $\Gamma_r^{\langle t \rangle}$ (see *eq.9-3*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}} &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t \rangle}} \frac{\partial \mathbf{z}_r^{\langle t \rangle}}{\partial \mathbf{x}^{\langle t \rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t \rangle}} \mathbf{W}_{rx}^{\intercal}\end{aligned}$$

Comp-2 flows-in as derivative from $\Gamma_u^{\langle t \rangle}$ (see *eq.9-2*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}} &= \frac{\partial J}{\partial \mathbf{z}_u^{\langle t \rangle}} \frac{\partial \mathbf{z}_u^{\langle t \rangle}}{\partial \mathbf{x}^{\langle t \rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_r^{\langle t \rangle}} \mathbf{W}_{ux}^{\intercal}\end{aligned}$$

Comp-3 flows-in as derivative from $\tilde{\mathbf{c}}^{\langle t \rangle}$ (see *eq.9-2*), and is computed as follows

$$\begin{aligned}\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}} &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t \rangle}} \frac{\partial \mathbf{z}_c^{\langle t \rangle}}{\partial \mathbf{x}^{\langle t \rangle}} \\ &= \frac{\partial J}{\partial \mathbf{z}_c^{\langle t \rangle}} \mathbf{W}_{cx}^{\intercal}\end{aligned}$$

These three components are then added to compute the true derivative, i.e.

$$\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}} = \left.\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}}\right|_{\textbf{Comp-1}} + \left.\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}}\right|_{\textbf{Comp-2}} + \left.\frac{\partial J}{\partial \mathbf{x}^{\langle t \rangle}}\right|_{\textbf{Comp-3}}$$

(see $\oplus$ labeled as *4*, and *6* in figure-2)

4 Gradient or Jacobian?

In the above derivations, we have used the numerator layout while performing matrix-derivatives. One of the consequences of this decision is that the derivatives that we have computed are in-fact jacobians and not gradients. Fortunately, gradients are just transpose of jacobians.