Incremental Semantic Dependency Parsing

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Introduction

The person who officials say ___ stole millions ...

Goal

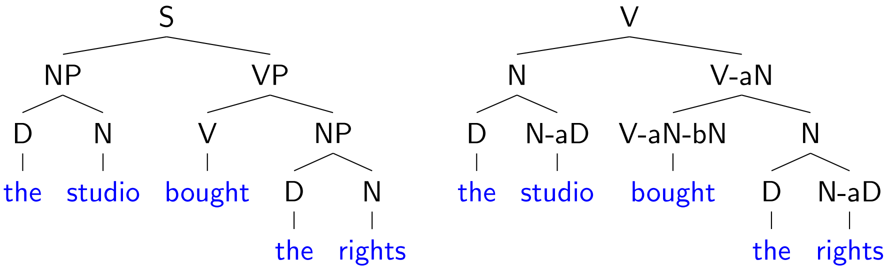
- Incrementally obtain correct parse despite filler-gap
- Test claims about human processing

Introduction

Previous studies [Gibson, 2000, Chen et al., 2005] have found filler-gap dependencies incur processing costs.
These studies conflate processing center embeddings with processing filler-gap constructions.

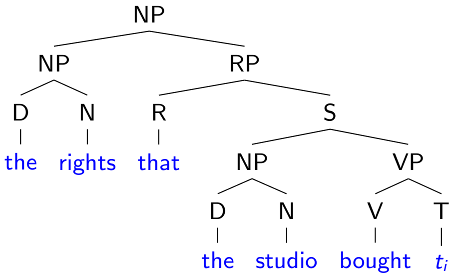
Training

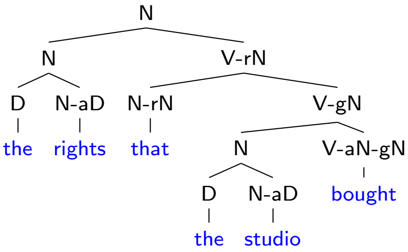
Reannotate WSJ [Nguyen et al., 2012]



Training

We can also keep the WSJ traces around.





Interpretation: Reannotation Rules

$$\frac{g{:}d \quad h{:}\, c\text{-}\mathbf{a}d}{(f_{c\text{-}\mathbf{ad}}\, g\, h){:}\, c} \quad \frac{g{:}d\psi \quad h{:}\, c\text{-}\mathbf{a}d}{\lambda_k\, (f_{c\text{-}\mathbf{ad}}\, (g\, k)\, h){:}\, c\psi} \quad \frac{g{:}d \quad h{:}\, c\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{ad}}\, g\, (h\, k)){:}\, c\psi} \quad \frac{g{:}d\psi \quad h{:}\, c\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{ad}}\, (g\, k)\, (h\, k)){:}\, c\psi}$$

$$\frac{g{:}\, c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{bd}}\, g\, h){:}\, c} \quad \frac{g{:}\, c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\, (f_{c\text{-}\mathbf{bd}}\, (g\, k)\, h){:}\, c\psi} \quad \frac{g{:}\, c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{bd}}\, g\, (h\, k)){:}\, c\psi} \quad \frac{g{:}\, c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{bd}}\, (g\, k)\, (h\, k)){:}\, c\psi} \tag{Aa–h}$$

$$\frac{g{:}\, u\text{-}\mathbf{a}d \quad h{:}c}{(f_{\mathrm{IM}}\, g\, h){:}c} \quad \frac{g{:}\, u\text{-}\mathbf{a}d\psi \quad h{:}c}{\lambda_k\, (f_{\mathrm{IM}}\, (g\, k)\, h){:}c\psi} \quad \frac{g{:}\, u\text{-}\mathbf{a}d \quad h{:}c\psi}{\lambda_k\, (f_{\mathrm{IM}}\, g\, (h\, k)){:}c\psi} \quad \frac{g{:}\, u\text{-}\mathbf{a}d\psi \quad h{:}c\psi}{\lambda_k\, (f_{\mathrm{IM}}\, (g\, k)\, (h\, k)){:}c\psi}$$

$$\frac{g{:}c \quad h{:}\, u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\, g\, h){:}c} \quad \frac{g{:}c\psi \quad h{:}\, u\text{-}\mathbf{a}d}{\lambda_k\, (f_{\mathrm{FM}}\, (g\, k)\, h){:}c\psi} \quad \frac{g{:}c \quad h{:}\, u\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{\mathrm{FM}}\, g\, (h\, k)){:}c\psi} \quad \frac{g{:}c\psi \quad h{:}\, u\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{\mathrm{FM}}\, (g\, k)\, (h\, k)){:}c\psi} \tag{Ma–h}$$

$$\frac{g{:}\, c\text{-}\mathbf{a}d}{\lambda_k\, (f_{c\text{-}\mathbf{ad}}\, \{k\}\, g){:}\, c\text{-}\mathbf{g}d} \quad \frac{g{:}\, c\text{-}\mathbf{b}d}{\lambda_k\, (f_{c\text{-}\mathbf{ad}}\, \{k\}\, g){:}\, c\text{-}\mathbf{g}d} \quad \frac{g{:}c}{\lambda_k\, (f_{\mathrm{IM}}\, \{k\}\, g){:}c\text{-}\mathbf{g}d} \tag{Ga–c}$$

$$\frac{g{:}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_i\, \exists_j\, (g\, i) \wedge (h\, i\, j){:}e} \quad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_{k\,j}\, \exists_i\, (g\, k\, i) \wedge (h\, i\, j){:}\, c\text{-}\mathbf{r}e} \quad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_{k\,j}\, \exists_i\, (g\, k\, i) \wedge (h\, i\, j){:}\, c\text{-}\mathbf{i}e} \tag{Fa–c}$$

$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\, \exists_j\, (g\, i) \wedge (h\, i\, j){:}e} \tag{R}$$

Interpretation: Reannotation Rules

$$\frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d}{(f_{c\text{-}\mathbf{ad}}\; g\; h){:}\,c} \qquad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\;k)\;h){:}\,c\psi} \qquad \frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\;g\;(h\;k)){:}\,c\psi} \qquad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\;k)\;(h\;k)){:}\,c\psi}$$

$$\frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{bd}}\; g\; h){:}\,c} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\;k)\;h){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\;g\;(h\;k)){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\;k)\;(h\;k)){:}\,c\psi} \tag{Aa–h}$$

$$\frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c}{(f_{\mathrm{IM}}\; g\; h){:}c} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,(g\;k)\;h){:}c\psi} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\;g\;(h\;k)){:}c\psi} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\,(g\;k)\;(h\;k)){:}c\psi}$$

$$\frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\; g\; h){:}c} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d}{\lambda_k\,(f_{\mathrm{FM}}\,(g\;k)\;h){:}c\psi} \qquad \frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\;g\;(h\;k)){:}c\psi} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,(g\;k)\;(h\;k)){:}c\psi} \tag{Ma–h}$$

$$\frac{g{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\;g){:}\,c\text{-}\mathbf{g}d} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\;g){:}\,c\text{-}\mathbf{g}d} \qquad \frac{g{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,\{k\}\;g){:}c\text{-}\mathbf{g}d} \tag{Ga–c}$$

$$\frac{g{:}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_i\,\exists_j\,(g\;i) \wedge (h\;i\;j){:}e} \qquad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i) \wedge (h\;i\;j){:}\,c\text{-}\mathbf{r}e} \qquad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i) \wedge (h\;i\;j){:}\,c\text{-}\mathbf{i}e} \tag{Fa–c}$$

$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\,\exists_j\,(g\;i) \wedge (h\;i\;j){:}e} \tag{R}$$

Interpretation: Reannotation Rules

$$\frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d}{(f_{c\text{-}\mathbf{ad}}\,g\,h){:}\,c} \quad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\,k)\,h){:}\,c\psi} \quad \frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,g\,(h\,k)){:}\,c\psi} \quad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\,k)\,(h\,k)){:}\,c\psi}$$

$$\frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{bd}}\,g\,h){:}\,c} \quad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\,k)\,h){:}\,c\psi} \quad \frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,g\,(h\,k)){:}\,c\psi} \quad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\,k)\,(h\,k)){:}\,c\psi} \tag{Aa–h}$$

$$\frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c}{(f_{\mathrm{IM}}\,g\,h){:}c} \quad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,(g\,k)\,h){:}c\psi} \quad \frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\,g\,(h\,k)){:}c\psi} \quad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\,(g\,k)\,(h\,k)){:}c\psi}$$

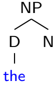
$$\frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\,g\,h){:}c} \quad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d}{\lambda_k\,(f_{\mathrm{FM}}\,(g\,k)\,h){:}c\psi} \quad \frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,g\,(h\,k)){:}c\psi} \quad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,(g\,k)\,(h\,k)){:}c\psi} \tag{Ma–h}$$

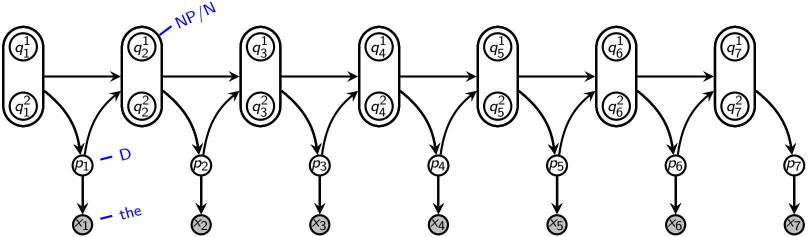
$$\frac{g{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\;g){:}\,c\text{-}\mathbf{g}d} \quad \frac{g{:}\,c\text{-}\mathbf{b}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\,g){:}\,c\text{-}\mathbf{g}d} \quad \frac{g{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,\{k\}\,g){:}c\text{-}\mathbf{g}d} \tag{Ga–c}$$

$$\frac{g{:}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_i\,\exists_j\,(g\,i) \wedge (h\,i\,j){:}e} \quad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\,k\,i) \wedge (h\,i\,j){:}\,c\text{-}\mathbf{r}e} \quad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\,k\,i) \wedge (h\,i\,j){:}\,c\text{-}\mathbf{i}e} \tag{Fa–c}$$

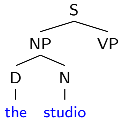
$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\,\exists_j\,(g\,i) \wedge (h\,i\,j){:}e} \tag{R}$$

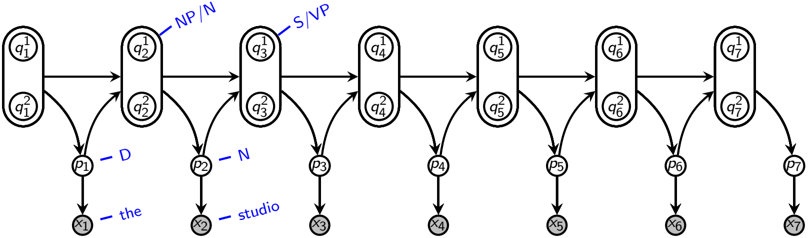
Practice Parse #1364



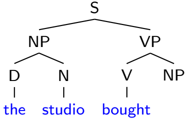


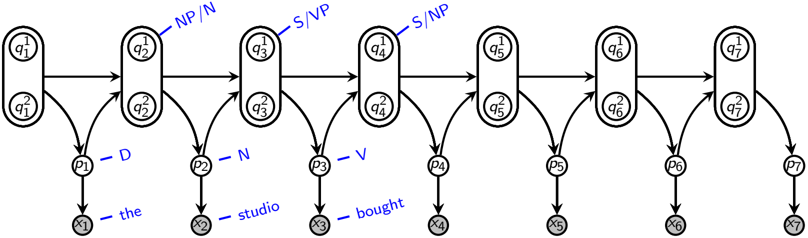
Practice Parse #1364



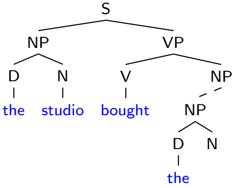


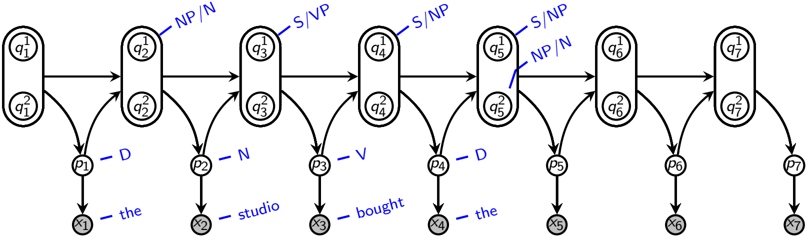
Practice Parse #1364



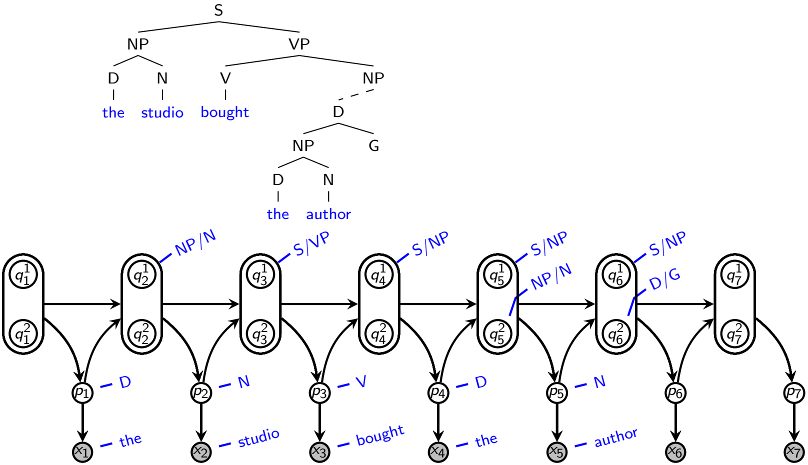


Practice Parse #1364

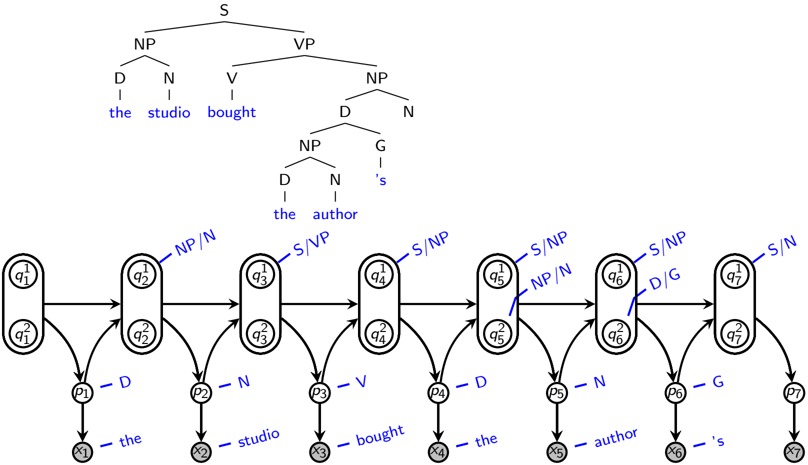




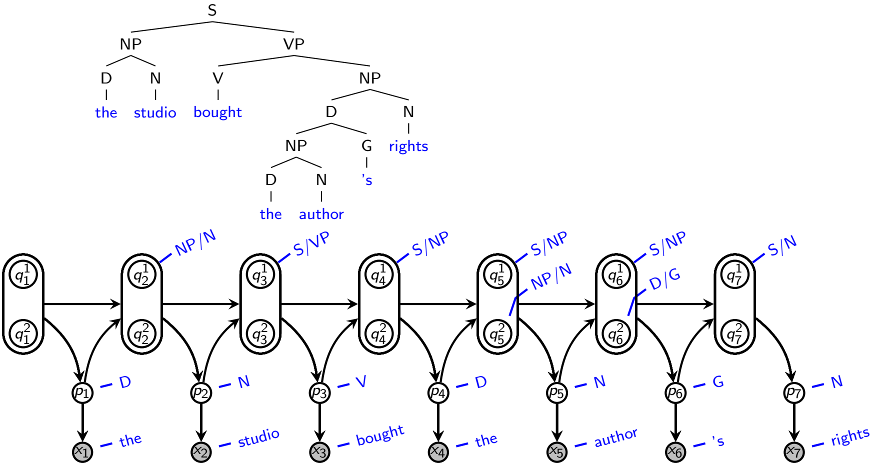
Practice Parse #1364



Practice Parse #1364

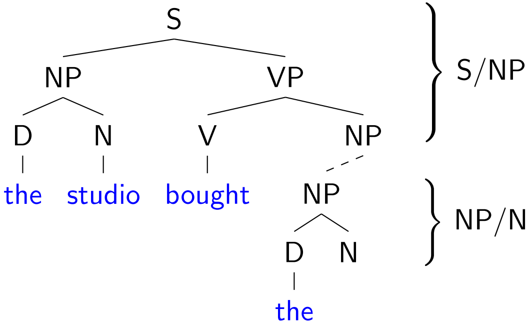


Practice Parse #1364



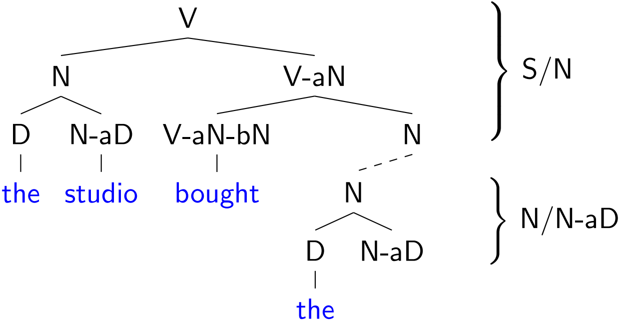
Interpretation

Connected Components

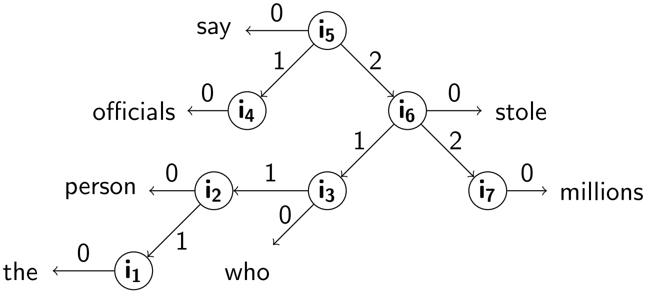


Interpretation

Reannotated Connected Components



Interpretation: Referent States



Interpretation: Fa/La

First or Last element of a CC

$$\frac{\exists_{i^1 j^1 .. \, i^\ell j^\ell} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\, i^\ell) \quad x_t}{\exists_{i^1 j^1 .. \, i^\ell} \; \ldots \; \wedge \; ((g^\ell f){:}c\, i^\ell)} \quad x_t \mapsto_M f{:}d \qquad (\text{–Fa})$$

$$\frac{\exists_{i^1 j^1 .. \, i^\ell j^\ell} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\, i^\ell) \quad x_t}{\exists_{i^1 j^1 .. \, i^\ell j^\ell i^{\ell+1}} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\, i^\ell) \; \wedge \; (f{:}e\, i^{\ell+1})} \quad x_t \mapsto_M f{:}e \qquad (+\text{Fa})$$

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^\ell{:}d\, i^\ell)}{\exists_{i^1 j^1 .. \, i^\ell j^\ell} \; \ldots \; \wedge \; ((f g^\ell){:}c/e\,\{j^\ell\}\, i^\ell)} \begin{cases} g{:}d \;\; h{:}e \Rightarrow (f\; g\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; (g\; k)\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; g\; (h\; k)){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; (g\; k)\; (h\; k)){:}c \end{cases} \qquad (\text{–La})$$

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^{\ell-1}{:}a/c\,\{j^{\ell-1}\}\, i^{\ell-1}) \; \wedge \; (g^\ell{:}d\, i^\ell)}{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1}} \; \ldots \; \wedge \; (g^{\ell-1} \circ (f\; g^\ell){:}a/e\,\{j^{\ell-1}\}\, i^{\ell-1})} \begin{cases} g{:}d \;\; h{:}e \Rightarrow (f\; g\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; (g\; k)\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; g\; (h\; k)){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k(f\; (g\; k)\; (h\; k)){:}c \end{cases} \qquad (+\text{La})$$

Interpretation

$$\frac{\exists_{i_1}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \qquad \text{the}}{\exists_{i_1\,i_3}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/N\text{-}aD}\,\{\mathbf{i_3}\}\,\mathbf{i_3}) \qquad \text{person}}\ {\scriptstyle +Fa,-La,-N}$$

$$\frac{}{\exists_{i_1\,i_3}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/V\text{-}rN}\,\{\mathbf{i_3}\}\,\mathbf{i_3}) \qquad \text{who}}\ {\scriptstyle -Fa,-La,-N}$$

$$\frac{}{\exists_{i_1\,i_3\,i_6}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/V\text{-}gN}\,\{\mathbf{i_6}\}\,\mathbf{i_3}) \qquad \text{officials}}\ {\scriptstyle +Fa,+Lc,-N}$$

$$\frac{}{\exists_{i_1\,i_3\,i_6\,i_9}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/V\text{-}gN}\,\{\mathbf{i_6}\}\,\mathbf{i_3})\ \wedge\ (..:\mathbf{V\text{-}gN/V\text{-}aN\text{-}gN}\,\{\mathbf{i_9}\}\,\mathbf{i_9}) \qquad \text{say}}\ {\scriptstyle +Fa,-La,-N}$$

$$\frac{}{\exists_{i_1\,i_3\,i_{11}}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/V\text{-}aN}\,\{\mathbf{i_{11}}\}\,\mathbf{i_3}) \qquad \text{stole}}\ {\scriptstyle +Fb,+La,+N}$$

$$\frac{}{\exists_{i_1\,i_3\,i_{13}}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})\ \wedge\ (..:\mathbf{N/N}\,\{\mathbf{i_{13}}\}\,\mathbf{i_3}) \qquad \text{millions}}\ {\scriptstyle +Fa,+La,-N}$$

$$\frac{}{\exists_{i_1}\ (..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})}\ {\scriptstyle -Fa,+La,-N}$$

Interpretation: Fb/Lb

$$\psi \in \{\text{-r,-i}\} \times \text{C}$$

$$\frac{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \quad x_t}{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge ((g^\ell(f'\{j^n\}f)){:}c\,i^\ell)}$$

$$x_t \mapsto_M \lambda_k(f'\{k\}\,f){:}d \quad (\text{–Fb})$$

$$\frac{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \quad x_t}{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^\ell j^\ell i^{\ell+1}} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \wedge ((f'\{j^n\}f){:}e\,i^{\ell+1})}$$

$$x_t \mapsto_M \lambda_k(f'\{k\}\,f){:}e \quad (+\text{Fb})$$

$$\frac{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^{\ell-1} j^{\ell-1} i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}d\,i^\ell)}{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge ((fg^\ell) \circ (f'\{j^n\}){:}c\psi/e\,\{j^\ell\}\,i^\ell)}$$

$$g{:}d\ \ h{:}e \Rightarrow \lambda_k(fg\,(f'\{k\}\,h)){:}c\psi \quad (\text{–Lb})$$

$$\frac{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^{\ell-1} j^{\ell-1} i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^{\ell-1}{:}a/c\psi\,\{j^{\ell-1}\}\,i^{\ell-1}) \wedge (g^\ell{:}d\,i^\ell)}{\exists_{i^1 j^1 ..\ i^n j^n ..\ i^{\ell-1} j^{\ell-1}} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^{\ell-1} \circ (fg^\ell) \circ (f'\{j^n\}){:}a/e\,\{j^{\ell-1}\}\,i^{\ell-1})}$$

$$g{:}d\ \ h{:}e \Rightarrow \lambda_k(fg\,(f'\{k\}\,h)){:}c\psi \quad (+\text{Lb})$$

Interpretation: Lc/N

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^{\ell}} \; \dots \; \wedge \; (g^{\ell}{:}d \; i^{\ell})}{\exists_{i^1 j^1 .. \, i^{\ell} j^{\ell}} \; \dots \; \wedge \; ((fg^{\ell}) \circ (\lambda_{h\,k\,i} \, (h\,k)){:}a/e\psi \, \{j^{\ell}\} \, i^{\ell})} \quad g{:}d \;\; h{:}e\psi \Rightarrow (fg \; h){:}c \tag{$-$Lc}$$

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^{\ell}} \; \dots \; \wedge \; (g^{\ell-1}{:}a/c \, \{j^{\ell-1}\} \, i^{\ell-1}) \; \wedge \; (g^{\ell}{:}d \; i^{\ell})}{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1}} \; \dots \; \wedge \; (g^{\ell-1} \circ (fg^{\ell}) \circ (\lambda_{h\,k\,i} \, (h\,k)){:}a/e\psi \, \{j^{\ell-1}\} \, i^{\ell-1})} \quad g{:}d \;\; h{:}e\psi \Rightarrow (fg \; h){:}c \tag{+Lc}$$

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell} j^{\ell}} \; \dots \; \wedge \; (g^{\ell-1}{:}c/d\psi \, \{j^{\ell-1}\} \, i^{\ell-1}) \; \wedge \; (g^{\ell}{:}d\psi/e \, \{j^{\ell}\} \, i^{\ell})}{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1}} \; \dots \; \wedge \; (g^{\ell-1} \circ (\lambda_{h\,i} \exists_j (h\,j)) \circ g^{\ell}{:}c/e \, \{j^{\ell-1}\} \, i^{\ell-1})} \tag{+N}$$

All of these rules may be made probabilistic

Interpretation

$$\exists_{i_1}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \quad \text{the}$$

$$+\text{Fa},-\text{La},-\text{N}$$

$$\exists_{i_1\,i_3}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/N\text{-}aD}\,\{\mathbf{i_3}\}\,\mathbf{i_3}) \quad \text{person}$$

$$-\text{Fa},-\text{La},-\text{N}$$

$$\exists_{i_1\,i_3}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/V\text{-}rN}\,\{\mathbf{i_3}\}\,\mathbf{i_3}) \quad \text{who}$$

$$+\text{Fa},+\text{Lc},-\text{N}$$

$$\exists_{i_1\,i_3\,i_6}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/V\text{-}gN}\,\{\mathbf{i_6}\}\,\mathbf{i_3}) \quad \text{officials}$$

$$+\text{Fa},-\text{La},-\text{N}$$

$$\exists_{i_1\,i_3\,i_6\,i_9}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/V\text{-}gN}\,\{\mathbf{i_6}\}\,\mathbf{i_3}) \;\wedge\; (..:\mathbf{V\text{-}gN/V\text{-}aN\text{-}gN}\,\{\mathbf{i_9}\}\,\mathbf{i_9}) \quad \text{say}$$

$$+\text{Fb},+\text{La},+\text{N}$$

$$\exists_{i_1\,i_3\,i_{11}}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/V\text{-}aN}\,\{\mathbf{i_{11}}\}\,\mathbf{i_3}) \quad \text{stole}$$

$$+\text{Fa},+\text{La},-\text{N}$$

$$\exists_{i_1\,i_3\,i_{13}}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1}) \;\wedge\; (..:\mathbf{N/N}\,\{\mathbf{i_{13}}\}\,\mathbf{i_3}) \quad \text{millions}$$

$$-\text{Fa},+\text{La},-\text{N}$$

$$\exists_{i_1}\,(..:\mathbf{T/T}\,\{\mathbf{i_1}\}\,\mathbf{i_1})$$

Evaluation: Syntactic vs Semantic

Syntactic Parser [van Schijndel et al., ress]

- Only Fa/La
- Trained on WSJ 02-21
- Split-merged $\times 5$ [Petrov et al., 2006]

Semantic Parser

- Trained on Reannotated WSJ 02-21
- Split-merged $\times 3$

Evaluation: Syntactic vs Semantic

Test Corpus: Dundee

- Log-transformed go-past durations
- Omit:
  - first and last of each line (wrap-up)
  - <5 times in WSJ (accuracy) [Fossum and Levy, 2012]
  - saccade length > 4 (track loss) [Demberg and Keller, 2008]

Evaluation: Syntactic vs Semantic

Linear Mixed Effects Baseline

- Number of characters
- Previous (next) word fixated?
- Unigram and Bigram probs
- Sentence position
- Total Surprisal [Hale, 2001]
- Number of intervening words
- Cum. Total Surprisal
- Cum. Entropy Reduction [Hale, 2003]
- Joint interactions
- Spillover Predictors

Factors are residualized off next simpler model
Subject and Item random intercepts were included

Evaluation: Syntactic vs Semantic

AIC and p-values

AIC can be used to test null hypothesis [Burnham and Anderson, 2002]

$\exp((- |\mathrm{AIC}_A - \mathrm{AIC}_B|)/2)$

Model	log-likelihood	AIC
syntactic	-74312	148874
semantic	-74314	148877
syntactic+(F–L+)	-74281	148816
semantic+(F–L+)	**-74277**	**148809**

Goodness-of-fits

Upper rows: Baseline comparison ($p = .14$)

Lower rows: With integration (F–L+) cost ($p = .03$)

Not shown: With encoding (F+L–) cost ($p = .14$)

Evaluation: Semantic Factor Correlations

Factor	t-score	p-value
F+L– (encoding)	4.17	$3.05 \cdot 10^{-05}$
F–L+ (integration)	-8.16	$3.38 \cdot 10^{-16}$

Significance of residualized factors on reading time.

Positive t-score: inhibition

Negative t-score: facilitation

Conclusion

Results

- Described incremental semantic dependency parser
- General metrics are not hurt by semantic calculation
- Semantic metrics predict reading times better than syntactic
- Replicated negative integration cost without FG confound

Fin

Thanks to Elliot Schumacher (and viewers like you)!
Questions?

Extras 1: Probabilistic Formulae

$$\mathsf{P}_{\phi_\ell}(\text{`}-\text{'}\ r^F \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{0} d\ \ldots) \cdot \textstyle\sum_x \mathsf{P}_\gamma(d \rightarrow x) \cdot [\![ r^F = \langle i, \text{`id'}, j\rangle]\!] \tag{1a}$$

$$\mathsf{P}_{\phi_\ell}(\text{`}+\text{'}\ r^F \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{+} d\ \ldots) \cdot \textstyle\sum_x \mathsf{P}_\gamma(d \rightarrow x) \cdot [\![ r^F = \langle \text{`}-\text{'}, \text{`}-\text{'}, \text{`}-\text{'}\rangle]\!] \tag{1b}$$

$$\mathsf{P}_{\lambda_\ell}(\text{`}+\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \textstyle\sum_{c',e} \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{0} c'\ \ldots) \cdot \mathsf{P}_{\gamma_{B,\ell}}(c' \rightarrow d\ e) \tag{2a}$$

$$\mathsf{P}_{\lambda_\ell}(\text{`}-\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \textstyle\sum_{c',e} \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{+} c'\ \ldots) \cdot \mathsf{P}_{\gamma_{A,\ell}}(c' \rightarrow d\ e) \tag{2b}$$

$$\mathsf{P}_{\nu_\ell}(\text{`}+\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle\ \langle j',d'\rangle\ \langle k,e\rangle) \overset{\text{def}}{=} [\![c,d,d' \in C \times \{\textbf{-g}\} \times C \ \wedge\ e \notin C \times \{\textbf{-g}\} \times C]\!] \tag{3a}$$

$$\mathsf{P}_{\nu_\ell}(\text{`}-\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle\ \langle j',d'\rangle\ \langle k,e\rangle) \overset{\text{def}}{=} [\![c,d,d' \notin C \times \{\textbf{-g}\} \times C \ \vee\ e \in C \times \{\textbf{-g}\} \times C]\!] \tag{3b}$$

Extras 1: Probabilistic Formulae

$$\mathsf{P}_{\alpha_\ell}(\langle i',c'\rangle\ r^A \mid l\,\langle i,c\rangle\,\langle j,d\rangle) \overset{\text{def}}{\propto} \begin{cases}\text{if } l = \text{'+'} : \sum_e \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{+} c'\ \ldots)\cdot \mathsf{P}_{\gamma_{A,\ell}}(c' \to d\ e) \\ \text{if } l = \text{'–'}\ : [\![c' = d]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } l = \text{'+'} \vee [d \ldots \Rightarrow c'] \in \text{Ae–h,Me–h} : [\![i' = j]\!] \\ \text{if } l = \text{'–'} \wedge [d \ldots \Rightarrow c'] \in \text{Aa–d,Ma–d}\ : [\![i' = \mathbf{i}_{\mathbf{Z}+1}]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } l = \text{'+'} : [\![r^A = \langle i', \text{'id'}, j\rangle]\!] \\ \text{if } l = \text{'–'}\ : [\![r^A = \langle \text{'–'}, \text{'–'}, \text{'–'}\rangle]\!]\end{cases} \tag{1}$$

$$\mathsf{P}_{\beta_{s,\ell}}(\langle k,e\rangle\ r^B \mid \langle i,c\rangle\,\langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{P}_{\gamma_{s,\ell}}(c \to d\ e)\cdot \begin{cases}\text{if } [d\,e \Rightarrow c] \in \text{Aa–d,Ma–d} : [\![k = i]\!] \\ \text{if } [d\,e \Rightarrow c] \in \text{Ae–h,Me–h}\ : [\![k = \mathbf{i}_{\mathbf{Z}+1}]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } [d\,e \Rightarrow c] \in \text{Aa–d,Me–h} : [\![r^B = \langle k, V(e), j\rangle]\!] \\ \text{if } [d\,e \Rightarrow c] \in \text{Ae–h,Ma–d} : [\![r^B = \langle j, V(d), k\rangle]\!] \\ \text{if } [d\,e \Rightarrow c] \in \text{Fa–c} \quad : [\![r^B = \langle \text{'–'}, \text{'–'}, \text{'–'}\rangle]\!]\end{cases} \tag{2}$$

$$\mathsf{P}_{\kappa_\ell}(r^K \mid \langle i,c\rangle\,\langle i',c'\rangle\,\langle j,d\rangle\,\langle k,e\rangle) \overset{\text{def}}{=}$$
$$\begin{cases}\text{if } c \in C\times\{\textbf{-g}\}\times C \ \wedge\ \exists_{d'}\ d'\ e \Rightarrow c' \ \wedge\ [d \Rightarrow d'] \in \text{Ga–b} : [\![r^K = \langle i', V(d), i\rangle]\!] \\ \text{if } c \in C\times\{\textbf{-g}\}\times C \ \wedge\ \exists_{e'}\ d\ e' \Rightarrow c' \ \wedge\ [e \Rightarrow e'] \in \text{Ga–b} : [\![r^K = \langle i', V(e), i\rangle]\!] \\ \text{if } c \in C\times\{\textbf{-g}\}\times C \ \wedge\ \exists_{d'}\ d'\ e \Rightarrow c' \ \wedge\ [d \Rightarrow d'] \in \text{Gc} : [\![r^K = \langle i, 1, i'\rangle]\!] \\ \text{if } c \in C\times\{\textbf{-g}\}\times C \ \wedge\ \exists_{e'}\ d\ e' \Rightarrow c' \ \wedge\ [e \Rightarrow e'] \in \text{Gc} : [\![r^K = \langle i, 1, i'\rangle]\!] \\ \text{otherwise} : [\![r^K = \langle \text{'–'}, \text{'–'}, \text{'–'}\rangle]\!]\end{cases} \tag{3}$$

Extras 1: Probabilistic Formulae

$$\begin{aligned}
\mathsf{P}_{\sigma}(q_t^{1..N} \mid q_{t-1}^{1..N} x_{t-1}) &\stackrel{\text{def}}{=} \mathsf{P}_{\phi_\ell}(\text{'--'} \mid b_{t-1}^{\ell}\; x_{t-1}) \cdot \mathsf{P}_{\sigma'_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N}\; a_{t-1}^{\ell}) \\
&\quad + \mathsf{P}_{\phi_\ell}(\text{'+'} \mid b_{t-1}^{\ell}\; x_{t-1}) \cdot \mathsf{P}_{\sigma'_{\ell+1}}(q_t^{1..N} \mid q_{t-1}^{1..N}\; x_{t-1}); \quad \ell \stackrel{\text{def}}{=} \max\{\ell' \mid q_{t-1}^{\ell'} \neq \text{'--'}\} \qquad (4) \\
\mathsf{P}_{\sigma'_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a') &\stackrel{\text{def}}{=} \mathsf{P}_{\lambda_\ell}(\text{'+'} \mid b_{t-1}^{\ell-1}\; a') \cdot [\![a = a_{t-1}^{\ell-1}]\!] \cdot \mathsf{P}_{\beta_{\mathrm{B},\ell-1}}(b \mid b_{t-1}^{\ell-1}\; a') \cdot \mathsf{P}_{\sigma''_{\ell-1}}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') \\
&\quad + \mathsf{P}_{\lambda_\ell}(\text{'--'} \mid b_{t-1}^{\ell-1}\; a') \cdot \mathsf{P}_{\alpha_\ell}(a \mid b_{t-1}^{\ell-1}\; a') \cdot \mathsf{P}_{\beta_{\mathrm{A},\ell}}(b \mid a_t^{\ell}\; a') \cdot \mathsf{P}_{\sigma''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') \qquad (5) \\
\mathsf{P}_{\sigma''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') &\stackrel{\text{def}}{=} \mathsf{P}_{\nu_{\ell-1}}(\text{'+'} \mid a_{t-1}^{\ell-1}\; b_{t-1}^{\ell-1}\; a_{t-1}^{\ell}\; b) \cdot \mathsf{P}_{\kappa_{\ell-1}}(r^K \mid b_{t-1}^{n}\; b_{t-1}^{\ell}\; a'\; b) \cdot \mathsf{P}_{\sigma'''_{\ell-1}}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) \\
&\quad + \mathsf{P}_{\nu_{\ell-1}}(\text{'--'} \mid a_{t-1}^{\ell-1}\; b_{t-1}^{\ell-1}\; a_{t-1}^{\ell}\; b) \cdot \mathsf{P}_{\kappa_{\ell-1}}(r^K \mid b_{t-1}^{n}\; b_{t-1}^{\ell}\; a'\; b) \cdot \mathsf{P}_{\sigma'''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) \qquad (6) \\
\mathsf{P}_{\sigma'''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) &\stackrel{\text{def}}{=} [\![q_t^{1..\ell-1} = q_{t-1}^{1..\ell-1}]\!] \cdot [\![a_t^{\ell} = a]\!] \cdot [\![b_t^{\ell} = b]\!] \cdot [\![q_t^{\ell+1..N} = \text{'--'}]\!] \qquad (7)
\end{aligned}$$

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