Fragment Grammars: Productivity and Reuse in Language

 Timothy J. O’Donnell
 MIT
-ness
-ness

- circuitousness, grandness, orderliness, pretentiousness, cheapness, coolness, warmthness, ...
-ness

- circuitousness, grandness, orderliness, pretentiousness, cheapness, coolness, warmthness, ...

- Adj>N
-ness

- circuitousness, grandness, orderliness, pretentiousness, cheapness, coolness, warmness, ...
- Adj> N
- grand + -ness
-ness

- circuitousness, grandness, orderliness, pretentiousness, cheapness, coolness, warmness, ...
- Adj>N
- grand + -ness
- pine-scentedness
-ity
-ity

• verticality, tractability, severity, seniority, inanity, electricity, ...
-ity

• verticality, tractability, severity, seniority, inanity, electricity, ...

• Adj>N
-ity

• verticality, tractability, severity, seniority, inanity, electricity, ...

• Adj>N

• Stress change (e.g., normalness v. normality), vowel laxing (e.g., inane v. inanity)
-ity

- verticality, tractability, severity, seniority, inanity, electricity, ...
- Adj>N
- Stress change (e.g., normalness v. normality), vowel laxing (e.g., inane v. inanity)
- The red lantern indicated the ethnicity/ethnicness of the restaurant
-ity

- verticality, tractability, severity, seniority, inanity, electricity, ...
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- Stress change (e.g., normalness v. normality), vowel laxing (e.g., inane v. inanity)
- The red lantern indicated the ethnicity/ethnicness of the restaurant
- *pine-scentedity
-ity
-ity

• But ...
-ity

- But ...
  - -ile/-al/-able/-ic/-(i)an
-ity

- But ...
- -ile/-al/-able/-ic/-an
- Bayesable
-ity

• But ...
  • -ile/-al/-able/-ic/-(i)an
  • Bayesable
    • Bayesability
-ity

- But ...
  - -ile/-al/-able/-ic/-(i)an
  - *Bayesable*
    - *Bayesability*
  - *Coolity is not trying*  (from Huffington Post)
-th
-th

• warmth, width, truth, depth, ...
-th

- warmth, width, truth, depth, ...
- Adj>N
-th

- warmth, width, truth, depth, ...
- Adj>N
- heal/health, dead/death, young/youth, vile/filth, slow/sloth
-th

• warmth, width, truth, depth, ...

• Adj>N

• heal/health, dead/death, young/youth, vile/filth, slow/sloth

• weal?/wealth, ?wroth/wrath, ?merry/mirth
-th

- warmth, width, truth, depth, ...
- Adj>N
- heal/health, dead/death, young/youth, vile/filth, slow/sloth
- weal?/wealth, ?wroth/wrath, ?merry/mirth
- roomth, greenth
-th

• warmth, width, truth, depth, ...

• Adj>N

• heal/health, dead/death, young/youth, vile/filth, slow/sloth

• weal?/wealth, ?wroth/wrath, ?merry/mirth

• roomth, greenth

Many enjoy the warmth, Vikings prefer the coolth
Problem of Productivity
Problem of Productivity

• Which processes can be used to construct *novel* forms (e.g., -ness), which can only be *reused* in existing forms (e.g., -th)?
Problem of Productivity

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• How are such differences in productivity represented by the adult language user?
Problem of Productivity

- Which processes can be used to construct novel forms (e.g., -ness), which can only be reused in existing forms (e.g., -th)?

- How are such differences in productivity represented by the adult language user?

- How are such differences learned by the child?
Outline
Outline

1. The Proposal.
Outline

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2. Five Models of Productivity and Reuse.
Outline

1. The Proposal.
2. Five Models of Productivity and Reuse.
3. English Derivational Morphology
Outline

1. The Proposal.
2. Five Models of Productivity and Reuse.
3. English Derivational Morphology
4. Conclusion
Outline

1. The Proposal.

2. Five Models of Productivity and Reuse.

3. English Derivational Morphology

4. Conclusion
The Proposal
The Proposal

1. Formalization of **what** can be reused.
The Proposal

1. Formalization of what can be reused.
   • Subcomputations.
The Proposal

1. Formalization of what can be reused.
   - Subcomputations.

2. Formalization of how decision to reuse versus compute is made.
The Proposal

1. Formalization of **what** can be reused.
   - Subcomputations.

2. Formalization of **how** decision to reuse versus compute is made.
   - Optimal Bayesian inference.
The Proposal

1. Formalization of **what** can be reused.
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3. The model from a probabilistic programming perspective.
The Proposal

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3. The model from a probabilistic programming perspective.
Starting Computational System

N → Adj
N → Adj -ness
N → Adj -ity
N → electro- N
N → magnet
N → dog
...
V → N -ify
V → Adj -ize
V → re- V
V → agree
V → count
...
Adj → dis- Adj
Adj → V -able
Adj → N -ic
Adj → N -al
Adj → tall
...
Adv → Adj -ly
Adv → today
...

N
|
---
Adj
|
|
V
|
|
-able
|
|
agree
Subcomputations

Diagram:

```
N  -ity
   /\  \\
Adj -able  \\
   |     \\
V   agree
```
Subcomputations
Subcomputations
The Proposal

1. Formalization of **what** can be reused.
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3. The model from a probabilistic programming perspective.
Bayesian Rational Analysis (Anderson, 1992)

• Find subcomputations which provide best explanation for the data.

• **What evidence** is available to the learner?
  - Which patterns give rise to productivity, which patterns imply reuse?
Subcomputations as Predictions

N

Adj

-able

V

agree

-ity
Prediction of future reusability across computations
Subcomputations as Predictions

Prediction of future reusability of combination

agree-able-ity
Subcomputations as Predictions

Prediction of future novelty/variability

N

Adj

-able

V

agree

-ity
Subcomputations as Predictions

Tradeoff between productivity and reuse

agree-able-ity

V | N
Adj
-able
N
-ity

Subcomputations as Predictions
The Proposal

1. Formalization of **what** can be reused.
   - Subcomputations.

2. Formalization of **how** decision to reuse versus compute is made.
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1. Formalization of **what** can be reused.
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2. Formalization of **how** decision to reuse versus compute is made.
   - Optimal Bayesian inference.

3. The model from a probabilistic programming perspective.
The Formal Model: *Fragment Grammars*
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- Generalization of *Adaptor Grammars* (Johnson et al., 2007).
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- Generalization of *Adaptor Grammars* (Johnson et al., 2007).
- Bayesian non-parametric distributions (*Pitman-Yor*).
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*Fragment Grammars*

- Generalization of *Adaptor Grammars* (Johnson et al., 2007).
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- Notion of *compiling* subcomputations via tools from probabilistic programming (*Church language; Goodman et al., 2008*).
The Formal Model:  *Fragment Grammars*

- Generalization of *Adaptor Grammars* (Johnson et al., 2007).
- Bayesian non-parametric distributions (*Pitman-Yor*).
- Notion of *compiling* subcomputations via tools from probabilistic programming (Church language; Goodman et al., 2008).
  - Stochastic memoization (Johnson et al., 2007) of stochastically lazy/eager programs.
Fragment Grammars via Probabilistic Programming (Church)
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• Alternative to more standard mathematical formalization (see, O’Donnell, 2011).
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• Highlights relationship between formalisms (PCFGs, Adaptor Grammars, Fragment Grammars).
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- Cross fertilization of ideas from the theory of programming languages.
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- Alternative to more standard mathematical formalization (see, O’Donnell, 2011).

- Highlights relationship between formalisms (PCFGs, Adaptor Grammars, Fragment Grammars).

- Cross fertilization of ideas from the theory of programming languages.

- Caveat: Church inference algorithms do not work well for these models.
Fragment Grammars via Probabilistic Programming
Fragment Grammars via Probabilistic Programming

1. Stochastic computation via unfold
Fragment Grammars via Probabilistic Programming

1. Stochastic computation via unfold

2. Stochastic reuse via memoization
Fragment Grammars via Probabilistic Programming

1. Stochastic computation via unfold

2. Stochastic reuse via memoization

3. Partial computations via stochastic laziness
Fragment Grammars via Probabilistic Programming

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Context Free Grammars

\[
\begin{align*}
W & \rightarrow N \\
W & \rightarrow V \\
W & \rightarrow Adj \\
W & \rightarrow Adv \\
N & \rightarrow Adj -ness \\
N & \rightarrow Adj -ity \\
N & \rightarrow electro- N \\
N & \rightarrow magnet \\
N & \rightarrow dog \\
\ldots \\
V & \rightarrow N -ify \\
V & \rightarrow Adj -ize \\
V & \rightarrow re- V \\
V & \rightarrow agree \\
V & \rightarrow count \\
\ldots \\
Adj & \rightarrow dis- Adj \\
Adj & \rightarrow V -able \\
Adj & \rightarrow N -ic \\
Adj & \rightarrow N -al \\
Adj & \rightarrow tall \\
\ldots \\
Adv & \rightarrow Adj -ly \\
Adv & \rightarrow today \\
\ldots 
\end{align*}
\]
Declarative Knowledge of Constituent Structure

<table>
<thead>
<tr>
<th>Rule</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{v1}$</td>
<td>W</td>
<td>N</td>
</tr>
<tr>
<td>$p_{v2}$</td>
<td>W</td>
<td>V</td>
</tr>
<tr>
<td>$p_{v3}$</td>
<td>W</td>
<td>Adj</td>
</tr>
<tr>
<td>$p_{v4}$</td>
<td>W</td>
<td>Adv</td>
</tr>
<tr>
<td>$p_{n1}$</td>
<td>N</td>
<td>Adj</td>
</tr>
<tr>
<td>$p_{n2}$</td>
<td>N</td>
<td>Adj</td>
</tr>
<tr>
<td>$p_{n3}$</td>
<td>N</td>
<td>electro-</td>
</tr>
<tr>
<td>$p_{n4}$</td>
<td>N</td>
<td>magnet</td>
</tr>
<tr>
<td>$p_{n5}$</td>
<td>N</td>
<td>dog</td>
</tr>
<tr>
<td>$p_{v1}$</td>
<td>V</td>
<td>N</td>
</tr>
<tr>
<td>$p_{v2}$</td>
<td>V</td>
<td>Adj</td>
</tr>
<tr>
<td>$p_{v3}$</td>
<td>V</td>
<td>re-</td>
</tr>
<tr>
<td>$p_{v4}$</td>
<td>V</td>
<td>agree</td>
</tr>
<tr>
<td>$p_{v5}$</td>
<td>V</td>
<td>count</td>
</tr>
<tr>
<td>$p_{adj1}$</td>
<td>Adj</td>
<td>dis-</td>
</tr>
<tr>
<td>$p_{adj2}$</td>
<td>Adj</td>
<td>V</td>
</tr>
<tr>
<td>$p_{adj3}$</td>
<td>Adj</td>
<td>N</td>
</tr>
<tr>
<td>$p_{adj4}$</td>
<td>Adj</td>
<td>N</td>
</tr>
<tr>
<td>$p_{adj5}$</td>
<td>Adj</td>
<td>tall</td>
</tr>
<tr>
<td>$p_{adv1}$</td>
<td>Adv</td>
<td>Adj</td>
</tr>
<tr>
<td>$p_{adv2}$</td>
<td>Adv</td>
<td>today</td>
</tr>
</tbody>
</table>

...
Declarative Knowledge of Constituent Structure

(define sample-rhs
  (lambda (nonterminal)
    (case nonterminal
      ((('W) (multinomial (list (list 'N) (list 'V) (list 'Adv) (list 'Adv) ... )
                  (list p w₁ p w₂ p w₃ p w₄ ...))))
       ((('N) (multinomial (list (list 'Adj 'ness) (list 'Adj 'ity) (list 'electro 'N) (list 'magnet) (list 'dog) ...)
                  (list p N₁ p N₂ p N₃ p N₄ p N₅ ...))))
       ((('V) (multinomial (list (list 'N 'ify) (list 'Adj 'ize) (list 're 'V) (list 'agree) (list 'count) ...)
                  (list p v₁ p v₂ p v₃ p v₄ p v₅ ...))))
       ((('Adj) (multinomial (list (list 'dis 'Adj) (list 'V 'able) (list 'N 'ic) (list 'N 'al) (list 'tall) ...)
                  (list p Adj₁ p Adj₂ p Adj₃ p Adj₄ p Adj₅ ...))))
       ((('Adv) (multinomial (list (list 'Adj 'ly) (list 'today) ...)
                  (list p w₁ p w₂ ...)))))))
Fundamental Recursive Computation: unfold

(define unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map unfold (sample-rhs symbol))))))
Fundamental Recursive Computation: \texttt{unfold}

\begin{verbatim}
(define unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map unfold (sample-rhs symbol))))))
\end{verbatim}

Choose a right-hand side for a symbol:

N $\rightarrow$ Adj -ity
Fundamental Recursive Computation: unfold

(define unfold
  (lambda (symbol)
    (if (terminal? symbol)
      symbol
      (map unfold (sample-rhs symbol))))))
Fundamental Recursive Computation: unfold

```
(define unfold
  (lambda (symbol)
    (if (terminal? symbol)
      symbol
      (map unfold (sample-rhs symbol)))))))
```

Recursively apply unfold to each symbol on right-hand side
Computation Trace

(unfold 'N)
Computation Trace

(unfold ‘N)

(define unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map unfold (sample-rhs symbol))))
Computation Trace

\[
\text{(unfold 'N)} \\
\text{(sample-rhs 'N)}
\]
Computation Trace

(unfold 'N)

(sample-rhs 'N)
Computation Trace

(unfold 'N)

(sample-rhs 'N)    N → Adj -ity
Computation Trace

(unfold 'N)

  (sample-rhs 'N)
Computation Trace

(sample-rhs 'N)

(unfold 'N)

(unfold 'Adj)  (unfold 'ity)
Computation Trace

```
(unfold 'N)
  |
(sample-rhs 'N)
  |
   (unfold 'Adj)  (unfold 'ity)
   |
     (sample-rhs 'Adj)
     |
       (unfold 'V)  (unfold 'able)
       |
         (sample-rhs 'V)  'able
         |
           (unfold 'agree)
           |
             'agree
```
Trace as Tree

N

Adj

-ity

V

-able

agree

(sample-rhs 'N)

(unfold 'N)

(sample-rhs 'Adj)

(unfold 'Adj)

(sample-rhs 'V)

(unfold 'V)

(sample-rhs 'agree)

('agree)

('able)

('ity)
Reusability for PCFGs
Fragment Grammars via Probabilistic Programming

1. Stochastic computation via unfold

2. Stochastic reuse via memoization

3. Partial computations via stochastic laziness
Memoization
Memoization

• Store outputs of earlier computations in a table
Memoization

- Store outputs of earlier computations in a table
- When function is called with particular arguments then grab from table if stored
Memoization

• Store outputs of earlier computations in a table
• When function is called with particular arguments then grab from table if stored
• When function is called with new arguments, then compute and store in table
Memoization

• Store outputs of earlier computations in a table

• When function is called with particular arguments then grab from table if stored

• When function is called with new arguments, then compute and store in table

• Higher-order function: \texttt{mem}
Reuse through Memoization

(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))
Reuse through Memoization

(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))

(eye-color 'bob) => 'blue
Reuse through Memoization

(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))

(eye-color 'bob) => 'blue
(eye-color 'bob) => 'brown
Reuse through Memoization

(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))

(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'brown
(eye-color 'bob)  => 'blue
Reuse through Memoization

(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))

(eye-color 'bob) => 'blue
(eye-color 'bob) => 'brown
(eye-color 'bob) => 'blue
(eye-color 'bob) => 'brown
(define eye-color
  (lambda (person)
    (if (flip 0.5) 'blue 'brown)))

(eye-color 'bob) => 'blue
(eye-color 'bob) => 'brown
(eye-color 'bob) => 'blue
(eye-color 'bob) => 'brown
...
Reuse through Memoization

(define eye-color
  (mem (lambda (person)
    (if (flip 0.5) 'blue brown))))
Reuse through Memoization

(define eye-color
  (mem (lambda (person)
         (if (flip 0.5) 'blue 'brown))))

Anywhere in the program where (eye-color 'bob) is used, we will reuse same value.
Reuse through Memoization

Anywhere in the program where (eye-color 'bob) is used, we will reuse same value.

(eye-color 'bob) => 'blue
Reuse through Memoization

(define eye-color
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Anywhere in the program where (eye-color 'bob) is used, we will reuse same value.

(eye-color 'bob) => 'blue
(eye-color 'bob) => 'blue
Reuse through Memoization

```
(define eye-color
  (mem (lambda (person)
         (if (flip 0.5) 'blue brown))))
```

Anywhere in the program where `(eye-color 'bob)` is used, we will reuse same value.

```
(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'blue
```
Reuse through Memoization

```
(define eye-color
  (mem (lambda (person)
         (if (flip 0.5) 'blue 'brown))))
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Anywhere in the program where `(eye-color 'bob)` is used, we will reuse same value.

- `(eye-color 'bob)` => 'blue
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(define eye-color
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Anywhere in the program where (eye-color 'bob) is used, we will reuse same value.

(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'blue
(eye-color 'bob)  => 'blue
...

Stochastic Reusability

- Deterministic memoization always returns same value after first call, but sometimes we want to **probabilistically** favor reuse.
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))

(location 'bob) => 'UCLA
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))

(location 'bob)  => 'UCLA
(location 'bob)  => 'Antarctica
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))

(location 'bob)  =>  'UCLA
(location 'bob)  =>  'Antarctica
(location 'bob)  =>  'London
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))

(location 'bob) => 'UCLA
(location 'bob) => 'Antarctica
(location 'bob) => 'London
(location 'bob) => 'Thailand
Stochastic Reusability

(define location
  (lambda (person)
    (sample-location-in-world)))

(location 'bob) => 'UCLA
(location 'bob) => 'Antarctica
(location 'bob) => 'London
(location 'bob) => 'Thailand
...

Stochastic Reusability

(define location
  (stochastic-mem (lambda (person)
                   (sample-location-in-world))))
Stochastic Reusability

(define location
  (stochastic-mem (lambda (person)
    (sample-location-in-world))))

(location 'bob) => 'home
Stochastic Reusability

(define location
  (stochastic-mem (lambda (person)
      (sample-location-in-world))))

(location 'bob) => 'home
(location 'bob) => 'office
Stochastic Reusability

(define location
  (stochastic-mem (lambda (person)
                    (sample-location-in-world)))))

(location 'bob)  => 'home
(location 'bob)  => 'office
(location 'bob)  => 'home
Stochastic Reusability

(define location
  (stochastic-mem (lambda (person)
    (sample-location-in-world)))))

(location 'bob) => 'home
(location 'bob) => 'office
(location 'bob) => 'home
(location 'bob) => 'home
Stochastic Reusability
Stochastic Memoization
(Goodman et al., 2008; Johnson et al., 2007)
Stochastic Memoization

(Goodman et al., 2008; Johnson et al., 2007)

- Adaptor Grammars: Anything that can be computed can be stored and reused probabilistically.
Stochastic Memoization
(Goodman et al., 2008; Johnson et al., 2007)

• Adaptor Grammars: Anything that can be computed can be stored and reused probabilistically.

• Memoization distribution: Pitman-Yor Processes (Pitman & Yor, 1995).
Stochastic Memoization
(Goodman et al., 2008; Johnson et al., 2007)

- Adaptor Grammars: Anything that can be computed can be stored and reused probabilistically.

- Memoization distribution: Pitman-Yor Processes (Pitman & Yor, 1995).

- Stochastic memoization + PCFGs = Adaptor Grammars.
Pitman-Yor Process
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process

• Two parameters:
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process

• Two parameters:
  • $a \in [0, 1]$
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process

• Two parameters:
  • $a \in [0, 1]$
  • $b > -a$
Pitman-Yor Process

- Generalization of the Chinese Restaurant Process
- Two parameters:
  - \( a \in [0, 1] \)
  - \( b > -a \)

Probability of Reuse

\[
\frac{y_i - a}{N + b}
\]
Pitman-Yor Process

- Generalization of the Chinese Restaurant Process
- Two parameters:
  - $a \in [0, 1]$
  - $b > -a$
- Probability of Reuse
  \[
  \frac{y_i - a}{N + b}
  \]
  \(y_i\): Total number of observations of value \(i\)
Pitman-Yor Process

- Generalization of the Chinese Restaurant Process

- Two parameters:
  - $a \in [0, 1]$
  - $b > -a$

Probability of Reuse

$$\frac{y_i - a}{N + b}$$

$y_i$: Total number of observations of value $i$

$N$: Total number of observations
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process

• Two parameters:
  • $a \in [0, 1]$
  • $b > -a$

Probability of Reuse

$$\frac{y_i - a}{N + b}$$

Probability of Novelty

$$\frac{a \cdot K + b}{N + b}$$

$y_i$: Total number of observations of value $i$
$N$: Total number of observations
Pitman-Yor Process

• Generalization of the Chinese Restaurant Process

• Two parameters:
  • $a \in [0,1]$
  • $b > -a$

Probability of Reuse

$$\frac{y_i - a}{N + b}$$

Probability of Novelty

$$\frac{a \cdot K + b}{N + b}$$

$y_i$: Total number of observations of value $i$
$N$: Total number of observations
$K$: Total number of values
Properties of PYPs
Properties of PYPs

• Rich get richer, concentrates distribution on a few values.
Properties of PYPs

• Rich get richer, concentrates distribution on a few values.

• Prefers fewer customers/tables/tables-per-customer.
Properties of PYPs

- Rich get richer, concentrates distribution on a few values.
- Prefers fewer customers/tables/tables-per-customer.
- Prefers to generate novel values proportional to how often novelty has been generated in the past.
Adaptor Grammars

(Johnson et al., 2007)

(define adapted-unfold
  (PYMem a b
    (lambda (symbol)
      (if (terminal? symbol)
          symbol
          (map unfold (sample-rhs symbol)))))))
Properties of Adaptor Grammars
Properties of Adaptor Grammars

• Reuse previous computations (subtrees).
Properties of Adaptor Grammars

- Reuse previous computations (subtrees).
- Can compute novel items productively using base system.
Properties of Adaptor Grammars

• Reuse previous computations (subtrees).
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• Only reuse complete subtrees (on adapted nonterminals).
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- Reuse previous computations (subtrees).
- Can compute novel items productively using base system.
- Build new stored trees recursively.
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\[
\begin{array}{c}
N \\
\text{Adj} & -ity \\
V & -able \\
\text{agree}
\end{array}
\]
Properties of Adaptor Grammars

- Reuse previous computations (subtrees).
- Can compute novel items productively using base system.
- Build new stored trees recursively.
- Only reuse complete subtrees (on adapted nonterminals).

```
N
  |   -ity
  Adj
  |
V -able
agree
```

```
N
  |   -ity
  Adj
  |
V -able
```
Reusability for Adaptor Grammars
Reusability for Adaptor Grammars

1. Always possible to use base grammar.
Reusability for Adaptor Grammars

1. Always possible to use base grammar.
2. Fully recursive.
Fragment Grammars via Probabilistic Programming

1. Stochastic computation via unfold

2. Stochastic reuse via memoization

3. Partial computations via stochastic laziness
Goal: Represent Partial Computations
Goal: Represent Partial Computations

Variables represent “delayed” instructions for later computation
Lazy and Eager Evaluation
Lazy and Eager Evaluation

- Eager Evaluation: Do as much work as early as possible.
Lazy and Eager Evaluation

• Eager Evaluation: Do as much work as early as possible.
• Lazy Evaluation: Delay work until it is absolutely necessary to continue computation.
Example

(define add3
  (lambda (x y z)
    (+ x y y z)))
Eager Evaluation

\((\text{add3} \ ( + \ 1 \ 2 \ 3 ) \ (* \ 2 \ 4 ) \ (- \ 3 \ 1 ))\)
Eager Evaluation

\((\text{add3} \ ( + \ 1 \ 2 \ 3 \)) \ (\ast \ 2 \ 4 \) \ (\text{-} \ 3 \ 1 ))\)
Eager Evaluation

\((\text{add3} \ 6 \ (* \ 2 \ 4) \ (- \ 3 \ 1))\)
Eager Evaluation

(add3 6 (* 2 4) (− 3 1))
Eager Evaluation

\[(\text{add3} \ 6 \ 8 \ (- \ 3 \ 1))\]
Eager Evaluation

\[(\text{add3} \ 6 \ 8 \ (- \ 3 \ 1))\]
Eager Evaluation

\((\text{add3} \ 6 \ 8 \ 2)\)
Eager Evaluation

```
(define add3
  (lambda (x y z)
    (+ x y z)))

(add3 6 8 2)
```
Eager Evaluation

\[(\text{define add3} \quad (\text{lambda} \ (x\ y\ z) \quad (+\ x\ y\ z)))\]

\[(+\ 6\ 8\ 2)\]
Eager Evaluation

16
Lazy Evaluation

(add3 (+ 1 2 3) (* 2 4) (− 3 1))
Lazy Evaluation

(define add3
  (lambda (x y z)
    (+ x y z)))

(add3 (+ 1 2 3) (* 2 4) (– 3 1))
Lazy Evaluation

\[
(\text{define add3} \\
(\text{lambda} \ (x\ y\ z) \\
(\text{+} \ x\ y\ z)))
\]

\[
( + \ ( + 1\ 2\ 3 ) \ ( * 2\ 4 ) \ ( - 3\ 1 ) )
\]
Lazy Evaluation

Argument expressions are delayed until their values are needed by another computation.
Lazy Evaluation

\[(+ ( + 1 2 3 ) (* 2 4 ) (- 3 1 ))\]

Primitive + procedure forces evaluation of arguments.
Lazy Evaluation

(+ (+ 1 2 3) (* 2 4) (− 3 1))
Lazy Evaluation

(+ 16 (* 2 4) (− 3 1))
Lazy Evaluation

(+ 16 (* 2 4) (– 3 1))
Lazy Evaluation

(+ 16 8 (− 3 1))
Lazy Evaluation

(+ 16 8 (− 3 1))
Lazy Evaluation

(+ 16 8 2)
Lazy Evaluation
λ-calculus: Order of Evaluation
\( \lambda \text{-calculus: Order of Evaluation} \)

- *Applicative order* (eager evaluation): evaluate arguments first, then apply function.
\[\lambda\text{-calculus: Order of Evaluation}\]

- **Applicative order** (eager evaluation): evaluate arguments first, then apply function.
- **Normal order** (lazy evaluation): copy arguments into procedure, only evaluate when needed.
\(\lambda\)-calculus: Order of Evaluation

- **Applicative order** (eager evaluation): evaluate arguments first, then apply function.
- **Normal order** (lazy evaluation): copy arguments into procedure, only evaluate when needed.
- **Church-Rosser theorem**: Order doesn’t matter for deterministic \(\lambda\)-calculus.
\( \lambda \)-calculus: Order of Evaluation

- **Applicative order** (eager evaluation): evaluate arguments first, then apply function.
- **Normal order** (lazy evaluation): copy arguments into procedure, only evaluate when needed.
- **Church-Rosser theorem**: Order doesn’t matter for deterministic \( \lambda \)-calculus.
- Does matter for \( \Psi \lambda \)-calculus!
Ψλ-calculus: Order of Evaluation

(define same? 
  (lambda (x) 
    (equal? x x))))
$\Psi\lambda$-calculus: Order of Evaluation

(define same? (lambda (x) (equal? x x)))
ψλ-calculus: Order of Evaluation

(define same?
  (lambda (x)
    (equal? x x)))

(same? (flip))
\(\Psi\lambda\)-calculus: Order of Evaluation

\[
(\text{define } \text{same}\? \text{ (lambda } (x) \\
(\text{equal}\? \ x \ x))
\]

\(P(\text{true}) = 1\)

\(\text{eager}\)

\(\text{same}\? \ (\text{flip})\)
\(\Psi\lambda\)-calculus: Order of Evaluation

\[
\text{(define same?} \\
\text{(lambda (x) } \\
\text{ (equal? x x)))}
\]

\[
\text{P(true) = 1/2}
\]

eager \quad P(true) = 1

\[
\text{(same? (flip))}
\]

lazy \quad P(true) = 1/2
• **Laziness** allows you to delay computation and, thus, *preserve randomness* and variability until the last possible moment.

• **Eagerness** allows you to determine random choices early in computation and, thus, *share* choices across different parts of a program.
Random Evaluation Order
Random Evaluation

Order

• Idea: Stochastically mix lazy and eager evaluation in $\Psi\lambda$-calculus.
Random Evaluation Order

- Idea: Stochastically mix lazy and eager evaluation in $\Psi\lambda$-calculus.

- Ultimately allow learning of which computations should be performed in advance and which should be delayed.
Random Evaluation Order

- Idea: Stochastically mix lazy and eager evaluation in $\Psi\lambda$-calculus.
- Ultimately allow learning of which computations should be performed in advance and which should be delayed.
- Assume eager evaluation strategy and add delay primitive.
Random Evaluation Order

- Idea: Stochastically mix lazy and eager evaluation in $\Psi\lambda$-calculus.
- Ultimately allow learning of which computations should be performed in advance and which should be delayed.
- Assume eager evaluation strategy and add delay primitive.
- Apply to unfold (can be applied fully generally).
Stochastic Lazy unfold

(define stochastic-lazy-unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map delay-or-unfold (sample-rhs symbol))))))
Stochastic Lazy unfold

(define stochastic-lazy-unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map delay-or-unfold (sample-rhs symbol)))))
Stochastic Lazy unfold

(define delay-or-unfold
  (lambda (symbol)
    (if (flip)
        (delay (stochastic-lazy-unfold symbol))
        (stochastic-lazy-unfold symbol)))))
Stochastic Lazy unfold

(define stochastic-lazy-unfold
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map delay-or-unfold (sample-rhs symbol))))))

(define delay-or-unfold
  (lambda (symbol)
    (if (flip)
        (delay (stochastic-lazy-unfold symbol))
        (stochastic-lazy-unfold symbol))))
Computation Trace with Delay

```
(unfold 'N)
  /
(sample-rhs 'N)
  /
(dealy-or-unfold 'Adj) (delay-or-unfold 'ity)
  /
(unfold 'Adj) (unfold 'ity)
  /
(sample-rhs 'Adj) 'ity
  /
(dealy-or-unfold 'V) (dealy-or-unfold 'able)
  /
(delay (unfold 'V)) (unfold 'able)
  /
'able
```
Computation Trace with Delay

```
(unfold 'N)
  | (sample-rhs 'N)
  |   | (dealy-or-unfold 'Adj)  | (dealy-or-unfold 'i!)
  |   | (unfold 'Adj)  | (delay-or-unfold 'i!)
  |   | (sample-rhs 'Adj)
  |   | (dealy-or-unfold 'V)  | (dealy-or-unfold 'able)
  |   | (delay (unfold 'V))  | (unfold 'able)
  |   |   | 'able
```

```
N
  | Adj
  |   -ity
  |   V
  |   -able
```
Reusing Delayed Computations
Reusing Delayed Computations

- Need to be able to reuse partial evaluations.
Reusing Delayed Computations

• Need to be able to reuse partial evaluations.

• Memoize stochastically lazy unfold.
Fragment Grammars

(define **stochastic-lazy-unfold**
  (lambda (symbol)
    (if (terminal? symbol)
        symbol
        (map delay-or-unfold (sample-rhs symbol))))
)

(define **delay-or-unfold**
  (PYMem a b (lambda (symbol)
    (if (flip)
        (if (flip)
            delay (stochastic-lazy-unfold symbol)
            (stochastic-lazy-unfold symbol)))
))))
Fragment Grammar
Reusable Computations
Fragment Grammar
Reusable Computations

1. Always possible to use base grammar.
1. Always possible to use base grammar.
2. Fully recursive.
Outline

1. The Proposal.
2. Five Models of Productivity and Reuse.
3. English Derivational Morphology
4. Conclusion
Five Models
Five Models

• 4 approaches to productivity and reuse.
Five Models

• 4 approaches to productivity and reuse.
• Capture historical proposals from the literature.
Five Models

• 4 approaches to productivity and reuse.
• Capture historical proposals from the literature.
• State-of-the-art probabilistic models.
Five Models

• 4 approaches to productivity and reuse.
• Capture historical proposals from the literature.
• State-of-the-art probabilistic models.
• Allow for variability and learning.
Multinomial-Dirichlet Context-Free Grammars
(Full-Parsing)

- All generalizations are productive
- Formalization: Multinomial-Dirichlet Probabilistic Context-free Grammar (MDPCFG; Johnson, et al. 2007a)
- Store whole form after first use.
- Always possible to compute productively with small probability; Fully recursive.
- Formalizes classic lexicalist theories (e.g., Jackendoff, 1975).

```
N
  Adj
  -ity
  N
  Adj
  -ness
  N
  Adj
  -ity
  N
  Adj
  -ity
```

```
V
  -able
  V
  -able
  V
  -able
  V
  -able
```
Store all generalizations consistent with input

Formalization: *Data-Oriented Parsing 1* (DOP1; Bod, 1998), *Data-Oriented Parsing: Goodman Estimator* (GDMN; Goodman, 2003)

Recently proposed as models of syntax (e.g., Snider, 2009; Bod, 2009)
- Store best set of subcomputations for explaining the data.
- Generalization of *Adaptor Grammars*
1. The Proposal.

2. Five Models of Productivity and Reuse.

3. English Derivational Morphology

4. Conclusion
# English Derivational Morphology

<table>
<thead>
<tr>
<th>Productive</th>
<th>+ness <em>(goodness)</em>, +ly <em>(quickly)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-productive</td>
<td>+ity <em>(ability)</em>, +or <em>(operator)</em></td>
</tr>
<tr>
<td>Unproductive</td>
<td>+th <em>(width)</em></td>
</tr>
</tbody>
</table>
Simulations

• Words from CELEX.
• Extensive heuristic parsing/hand correction.
• Input format.
  • No phonology or semantics.
Derivational Inputs

```
N
  /   \      /
Adj    -ity
    /
  V
agree

N
  /   \      /
V     ion
    /
  V
-ate
affirm
```
## English Derivational Morphology

<table>
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<td>+th (width)</td>
</tr>
</tbody>
</table>

1. Individual suffix productivity differences (-ness/-ity/-th).
2. Suffix sequences.
English Derivational Morphology

<table>
<thead>
<tr>
<th></th>
<th>+ness</th>
<th>+ly</th>
<th>+ity</th>
<th>+or</th>
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</tr>
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<td></td>
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<td></td>
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<td></td>
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<td>(operator)</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(width)</td>
</tr>
</tbody>
</table>

1. Individual suffix productivity differences (-ness/-ity/-th).

2. Suffix combinations.
Productivity

• No gold-standard dataset or measure.
  • E.g., Large databases of *wug*-tests or naturalness judgments.

• Analyses.
  1. Convergence with other theoretical measures.
How is Productivity Represented?

- Relative probability of fragments with or without variables.
Baayen’s Corpus-Based Measures

- Baayen’s $P/P^*$ (e.g., Baayen, 1992)

  - $P$: $\text{Prob(NOVEL} \mid \text{SUFFIX})$ i.e. rate of growth of forms with suffix
  
  - $P^*$: $\text{Prob(SUFFIX} \mid \text{NOVEL})$ i.e. rate of growth of vocabulary due to suffix
Productivity Correlations

\( \mathcal{P} / \mathcal{P}^* \) values from Hay & Baayen, 2002

<table>
<thead>
<tr>
<th>Model</th>
<th>FG (Inference-based)</th>
<th>MDPCFG (Full-parsing)</th>
<th>MAG (Full-listing)</th>
<th>DOPI (Exemplar-based)</th>
<th>GDMN (Exemplar-based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{P} )</td>
<td>0.907</td>
<td>-0.0003</td>
<td>0.692</td>
<td>0.346</td>
<td>0.143</td>
</tr>
<tr>
<td>( \mathcal{P}^* )</td>
<td>0.662</td>
<td>0.480</td>
<td>0.568</td>
<td>0.402</td>
<td>0.500</td>
</tr>
</tbody>
</table>
## English Derivational Morphology

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1. Individual suffix productivity differences (-ness/-ity/-th).
2. Suffix combinations.
Generalizable Combinations

Frozen Combinations

```
/\  
| V |
V--/-ate
    
affirm
```

Generalizable Combinations

```
/\  
| N |
V--/-ion
    
Adj--/-ity
    
V--/-able
```
Generalizable Combinations

Frozen Combinations

Generalizable Combinations

affirm

V

-ate

V

N

-ion

Adj

N

-ity

V

-able
-ity v. -ness

• -ness more productive than -ity.

• -ity more productive than -ness after: -ile, -able, -(i)an, -ic.

Two Frequent Combinations:
- ivity v. -bility

- **-ive + -ity:** *-ivity* (e.g., selectivity).
  - Speaker prefer to use -ness with novel words (Aronoff & Schvaneveldt, 1978).
  - depulsiveness > depulsivity.

- **-ble + -ity:** *-bility* (e.g., sensibility).
  - remortibility > remortibleness.
-ivity v. -bility

Predicted

Preference for -ness

-ive
-ble
-ness

-ity
-ivity v. -bility

Preference for -ity

-ive
-ble
-
ness

-ity
-ivity v. -bility

-ive

-ble

-ness

-ity

Preceding suffix -ive
-ivity v. -bility

Predicted

Preceding suffix -ble
Predicted MDPCFG

-ive
-ble

-ness

-ity

MDPCFG

(Full-parsing)

114
Predicted

MDPCFG (Full-parsing)

MAG (Full-listing)
Predicted MDPCFG (Full-parsing) MAG (Full-listing) DOPI (Exemplar-based)

-ive
-ble
-ness
-ity

ble ive ble ive ble ive ble ive
Discussion

- Inference-based approach able to correctly ignore high token frequency of -ivity because it balances a tradeoff.

- Other models use type or token frequencies.
Outline

1. The Proposal.
2. Five Models of Productivity and Reuse.
3. Empirical Evaluation
   - The English Past Tense
   - English Derivational Morphology
4. Conclusion
Conclusion
Conclusion

• View productivity and reuse as an inference.
Conclusion

• View productivity and reuse as an inference.

• Link between theory of programming languages and Bayesian models.
Conclusion

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• Able to capture dominant patterns \textbf{without} semantic and phonological structure.
Conclusion

• View productivity and reuse as an inference.

• Link between theory of programming languages and Bayesian models.

• Able to capture dominant patterns without semantic and phonological structure.

• Future work...
Thanks!