Design and Implementation of Anglican Probabilistic Programming Language

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https://bitbucket.org/probprog/anglican-white-paper
https://bitbucket.org/probprog/anglican
http://www.robots.ox.ac.uk/~fwood/anglican/index.html

Outline

Intuition

Probabilistic program:

- A program with random computations.
- Distributions are conditioned by 'observations'.
- Values of certain expressions are 'predicted' — **the output**.

Can be written in any language (extended by `sample` and `observe`).

Example: Model Selection

```
(let [;; Guessing a distribution
      dist (sample (categorical
                     [[normal 1] [gamma 1]
                      [uniform-continuous 1]
                      [uniform-discrete 1]]))
      a (sample (gamma 1 1))
      b (sample (gamma 1 1))
      d (dist a b)]
  ;; Observing samples from the distribution
  (loop [data data]
    (when (seq data)
      (let [[x & data] data]
        (observe d x))
      (recur data)))
  ;; Predicting a, b and the distribution
  (predict :a a)
  (predict :b b)
  (predict :d d))
```

More examples

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More examples

- *Intruder detection* — given a log of **times** and **amounts** of payments in a bank account, how likely that the baccount was compromised?
- *Counterfactual reasoning* — There are **two routes** from Jerusalem to Tel Aviv: 1 and 443. Based on traffic reports, I chose route 1 and was late. Would I arrive on time If I chose 443 instead?
- *(Due to Stuart Russell)* If you observe that a student GPA is exactly 4.0 in a model of transcripts of students from the USA (GPA's from 0.0 to 4.0) and India (GPA's from 0.0 to 10.0), what is the probability that the student is from India?

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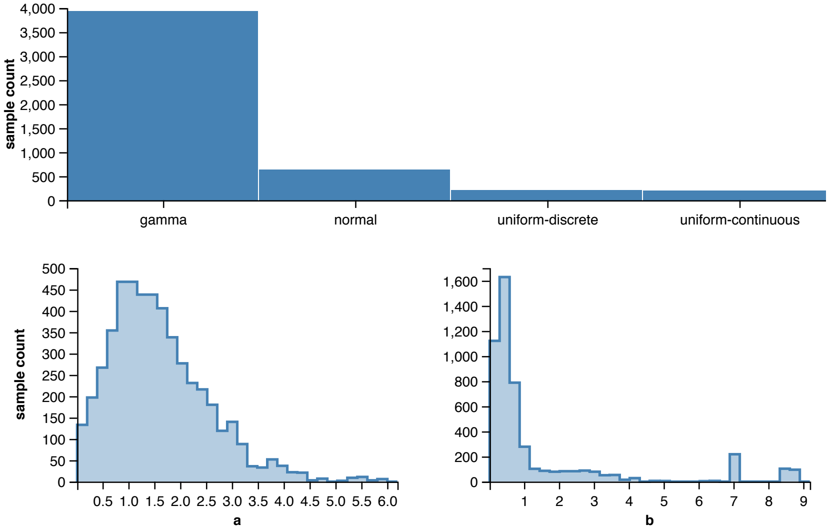
- Continuously and **infinitely generate a sequence of samples** drawn from the distribution of the output expression — so that someone else puts it in good use (vague but common). ✓

Example: Inference Results



Importance Sampling

loop
  Run program, computing weight based on observations.
  Output result and weight.
end loop

- Simple — good.
- Slow convergence (unless one knows the answer) — bad.

Can we do better?

Lightweight Metropolis-Hastings (LMH)

Run program once, remembering random choices.
loop
    Uniformly select one random choice.
    Propose a new value for the choice.
    Re-run the program.
    Accept or reject with MH probability.
    Output result.
end loop

Can we do better?

- Particle methods
- Variational inference
- ...

Why functional?

We want a functional language because an inference algorithm controls the execution:

- A program is run many (often many hundreds of thousands) of times (with almost any algorithm).
- A program must be partially re-executed multiple times from different positions (particle methods).
- We want to reason about the distribution defined by the program.

We need

- First-class functions.
- No side effects.

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- Scheme — (Church, Venture).
- Scala — Figaro.
- Haskell — Hakaru, Model-Bayes.
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As well as Python, C#, and other languages.

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Anglican is

- Integrated with Clojure.
- Shares syntax.
- Alters operational semantics.

Design challenges and choices

- Anglican syntax: Clojure + probabilistic constructs.
  - Subset of Clojure.
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- Source-to-source compilation of Anglican into Clojure.
  - CPS transformation, with some tricks.
  - Transparent use of Clojure functions from Anglican.
- Inference algorithms.
  - Required to run an Anglican program.
  - Step in at checkpoints (`sample` and `observe`).
  - Execute programs by calling continuations repeatedly.

The language

A subset of Clojure, wrapped inside `defquery`:

- `if`, `when`, `cond`, `case`, `let`, `and`, `or`, `fn`.
- Vector destructuring in bindings of `let` and `fn`.
- Compound literals for vectors, hash maps, and sets.
- `loop`/`recur` — a convenience.

Core library:

- All of Clojure core library, except for higher-order functions.
- `map`, `reduce`, `filter`, `some`, `repeatedly`, `comp`, `partial`.

Any Clojure function can be called from Anglican.

Macro-based compilation

Anglican code macro-compiled into Clojure, in CPS:

```
(loop [data data]
  (if (seq data)
    (let [[x & data] data]
      (observe (gamma a b) x)
      (recur data))
    (predict :a a)))
```

```
((fn loop [C23151 $state data]
   (if (seq data)
     (let [[x & data] data]
       (->observe '023153 (gamma a b) x
         (fn do23152 [_ $state]
           (loop C23151 $state data))
         $state))
     (fn []
       (C23151
         nil
         (add-predict $state :a a)))))
 cont $state data)
```

A continuation accepts *two* arguments:

- The computed value.
- The internal state (`$state`).

Functions accept continuation and state as two first arguments.

Outline

Motivation

Design Outline

Implementation Highlights

Inference Algorithms

Probabilistic forms

Two **probabilistic** forms:

- `sample` — draws a value from a distribution;
- `observe` — conditions the *a posteriori* distribution by observing a value from a distribution.

This is where the inference algorithm steps in:

```
=> (cps-of-expression '(sample dist) 'cont)
(->sample dist cont $state)

=> (cps-of-expression '(observe dist val) 'cont)
(->observe dist val cont $state)
```

Managing stack size

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The thunk is returned ...

```
(fn [x y] (+ x y))
```

```
(fn [cont $state x y]
  (fn []
    (cont (+ x y) $state)))
```

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(fn [cont $state x y]
  (fn []
    (cont (+ x y) $state)))
```

... and called by `trampoline`:

```
(defn exec
  [algorithm prog value state]
  (loop [step (trampoline prog value state)]
    (let [next (checkpoint algorithm step)]
      (if (fn? next)
        (recur (trampoline next))
        next))))
```

Memoization

Memoization of random choice:

- A person has a random eye color.
- But the *same* person has a fixed eye color.

```
(let [eye-color (mem (fn [person]
                       (sample
                         (categorical
                           ['brown 0.5]
                           ['green 0.5]))))]
  (if (not= (eye-color 'bill) (eye-color 'john))
    (predict (eye-color 'bill))
    (predict (eye-color 'john))))
```

Compiling a memoized function

```
(mem (fn [person] ...))
```

```
(fn []
 (cont
  ;; every memoization gets a unique key
  (let [M23145 (gensym "M")]
   (fn [C23144 $state & P23147]
    (if (in-mem? $state M23145 P23147)
     ;; previously memoized result
     (fn []
       (C23144
         (get-mem $state M23145 P23147)
         $state))
     ;; new computation
     (clojure.core/apply
      (fn [C23150 $state person]
        (fn [] (C23150 ... $state)))
      ;; memoize result in state
      (fn [V23146 $state]
       (fn []
        (C23144
          V23146
          (set-mem $state M23145 P23147 V23146))))
      $state
      P23147))))
  $state))
```

Outline

Importance sampling

Importance sampling is the simplest:

```
(defmethod infer :importance [_ prog value & {}]
  (letfn
    [(sample-seq []
       (lazy-seq
         (cons
           (:state (exec ::algorithm prog value
                               initial-state))
           (sample-seq))))]
    (sample-seq)))
```

Default checkpoint handlers are called:

```
(defmethod checkpoint [::algorithm anglican.trap.observe] [_ obs]
  #((:cont obs) nil (add-log-weight (:state obs)
                                    (observe* (:dist obs) (:value obs)))))

(defmethod checkpoint [::algorithm anglican.trap.sample] [_ smp]
  #((:cont smp) (sample* (:dist smp)) (:state smp)))
```

Other inference algorithms

- Implement `infer`.
- Redefine one or both checkpoints.
- An average implementation is ≈ 150 lines of Clojure code.
- A dozen different inference algorithms are in the code base.
- Half of them are really useful.

Recap

- Anglican is integrated with Clojure.
- Shares syntax but alters semantics.
- Macro-compiled.
- Efficient.
- Makes implementing AND using inference easy.

Thank you!

Questions?