Troll, a Language for specifying Dice-rolls

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Troll, a Language for Specifying Dice-Rolls

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ABSTRACT
Dice are used in many games, and often in fairly complex ways that make it difficult to unambiguously describe the dice-roll mechanism in plain language.

Many role-playing games, such as Dungeons & Dragons, use a formalised notation for some instances of dice-rolls. This notation, once explained, make dice-roll descriptions concise and unambiguous. Furthermore, the notation has been used in automated tools for pseudo-random dice-rolling (typically used when playing over the Internet).

This notation is, however, fairly limited in the types of dice-rolls it can describe, so most games still use natural language to describe rolls. Even Dungeons & Dragons use formal notation only for some of the dice-roll methods used in the game. Hence, a more complete notation is in this paper proposed, and a tool for pseudo-random rolls and (nearly) exact probability calculations is described.

The notation is called “Troll”, combining the initial of the Danish word for dice (“terninger”) with the English word “roll”. It is a development of the language Roll described in an earlier paper. The present paper describes the most important features of Troll and its implementation.

Categories and Subject Descriptors
D.3.2 [Programming Languages]: Language Classifications—Specialized application languages; G.3 [Probability and Statistics]: Distribution functions

General Terms
Languages

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Dice, Probability, Domain-Specific Languages

1. INTRODUCTION
The first thing to ask is: Why would you want a formal notation for specifying dice-rolls?

There are several answers to this:

- Formal notation can give a concise and unambiguous description which can be used to communicate ideas between people. This is, for example, the main motivation for mathematical notation. Games that use dice can (and sometimes do) use formal notation to describe dice-rolls.

- A formal notation is machine readable, which enables use of tools that analyse specifications of dice-rolls. Two types of tools are especially relevant for dice-rolls:

  Internet dice-roll servers for playing games that involve dice online or by email. There are many dice-roll servers, but they are each limited to a small number of different types of dice-roll. With a universal notation, a dice-roll server can perform rolls to any specification.

  Probability calculators As with any random element used in games, players and game designers are interested in knowing the probability of each possible outcome. A tool that takes a specification of a roll and calculates this is, hence, quite useful.

The concept of using formal notation for dice is not new: One of the first games to use a variety of dice shapes and rolling methods was Dungeons & Dragons from 1974 [3]. The rules introduced a formal notation for dice consisting of the following elements:

\[
d_n \text{ describes rolling a single dice with sides numbered } 1\text{–}n. \\
3d6 \text{, hence, denote rolling three six-sided dice and adding them up to get a result between 3 to 18.}
\]

In spite of introducing this notation, most of the rulebook used an alternative, less explanatory notation: An interval of values was shown, and it was up to the player to figure out which dice should be rolled to obtain this interval. For example, “3–18” would denote rolling and adding three six-sided dice, while “2–20” would denote rolling and adding two ten-sided dice.

In later editions, the \(mdn\) notation was used more and more, and in the most recent editions, the interval notation is completely eliminated. The \(mdn\) notation is also used in
other role-playing games and has been extended to include
addition, so you can write things like 2d8+1 or d6+d10. Ne-
evertheless, this extension is far from enough to describe dice-
roll methods used in modern role-playing games. Here are
some examples of methods from popular games:

- To determine values for personal characteristics such
  as strength and intelligence, Dungeons & Dragons sug-
gest several methods, one of which is to roll four six-
sided dice, discarding the lowest and adding the rest.

- “The World of Darkness” [1] lets a player roll a number
  of ten-sided dice equal to his ability score. If any of
  these show 10, additional dice equal to the number of
  10s are rolled. If some of these also show 10, this is
  repeated until no more 10s are rolled. At this point,
  the number of values exceeding 7 are counted to give
  the final value of the roll which, consequently, can be
  any number from 0 upwards.

- “Ironclaw” [4] lets a player roll three dice of different
  sizes (number of sides) determined by ability scores
  and count how many exceed a threshold determined
  by the difficulty of the task.

- “Silhouette” [13] lets a player roll a number of ten-
sided dice equal to his ability score and selects the
  highest of these as the result.

An universal method for dice-rolls needs to be able to de-
scribe all of the above, and more. Any Turing-complete
programming language can do this, but the result is not
necessarily very concise or readable, and it may be impos-
sible to analyse descriptions for such things as probability
distributions. Hence, we propose a notation that extends
the mdn notation from Dungeons & Dragons while being
readable to non-programmers after a short introduction.

This is not my first attempt at doing so: In 1996, I pro-
posed a notation called “Roll” [7], which attempted the same
thing. While it was moderately successful (it was used to
calculate probabilities when modifying rules for the new edi-
tion of “The World of Darkness” [1]), experiences showed
that the notation was not as readable to non-programmers
as it could be and that it lacked features to concisely de-
scribe some of the more complex rolls. To address this, Roll
was over time modified and extended until it had little re-
semblance to the original. Hence, a new name “Troll” was
chosen for the revised and extended language.

One of the key features of Troll (and Roll) is the ability
to automatically analyse descriptions for probability. Naive
calculation will in many instances be far too time-consuming,
so a number of optimisations are used. These are described
in section 4.

2. THE BASICS OF TROLL

When you roll several dice at the same dice, you don’t
normally care about any specific order, so it is natural to
consider the result of a dice-roll as a *multiset*, i.e., a collec-
tion where the order doesn’t matter but where multiplicity of
elements do. Multisets of integers are used throughout Troll
as the only data structure. Set operations like membership,
union, intersection and difference extend in the obvious way
to multisets. For details, see [17].

We will call a multiset of integers “a value”. A value con-
taining exactly one number will in some contexts be treated
as the number it contains. Some constructs require single-
ton values and run-time errors will be generated if these are
applied to non-singleton values. Likewise, some operations
require positive or non-negative numbers or non-empty mul-
tisets and will generate errors if applied to something other
than that.

Like in the original Dungeons & Dragons notation, dM
means rolling a die with n sides numbered from 1 to n.
However, mdn is the value (multiset) of m integers
obtained by rolling m n-sided dice, and you need an explicit sum opera-
tor to add up the numbers. Hence, what in Dungeons
& Dragons is written as just 3d6 will in Troll be written as
sum 3d6.

The reason for this is that, unlike in Dungeons & Dragons,
we need to do many other things to the dice than just add
them. For example, in Silhouette [13], we need to find the
maximum of n ten-sided dice, which we in Troll can write
as max n d10. There are also operators for finding the m
largest numbers in a value and for finding the minimum or
m smallest numbers. For example, the method mentioned
earlier for determining personal characteristics in Dungeons
& Dragons can be written as sum largest 3 d4d6.

When the number of dice rolled depends on in-game values
(such as ability level), it may be useful to use a variable
to represent the number of dice. For example, max n d10
will take the number of dice rolled from the variable n.1

Variables can be bound to values when running Troll or
locally inside definitions. We will return to this later.

Anywhere a number can occur in Troll, you can use an ex-
pression instead, so it is, for example, perfectly legal (though
not very sensical) to write d d10, which would roll a dice the
number of sides of which is determined by a d10. An expres-
sion like d(2d10) will, however, cause a run-time error, as
the d operator requires singletons as arguments. The usual
arithmetic operators on numbers, too, are defined only on
singleton arguments.

Like d can take a numeric prefix to specify the number of
rolls, you can specify multiple rolls of more complex expres-
sions by using the # operator: #sum 3d6 specifies a multiset
of six numbers each obtained by adding three dice2. You can
use set-like notation like [3,4,3] to build multisets. Union
of values is done using the infix operator . There has never
been any need for multiset intersection or difference when
defining rolls, so operators for these are not included in Troll.

2.1 Comparisons, conditionals and bindings

Some dice-roll mechanism, such as that described above
for Ironclaw [4], require the rolled numbers to be compared
against a threshold and counting of those that do.

Comparison is in Troll done by filters, that compare the ele-
ments of a value with a single number and only returns the
elements where the comparison holds. For example, 3<4d6
rolls four d6 and retains only those numbers n such that
3 < n. You can then count the number of remaining ele-
ments using the count operator, which simply returns the
number of elements in a value. So, an instance of the Silhou-
ette system where you roll one d8 and two d10 and where the
threshold is 5 can be written as count 5 <= {d8,d10,d10}. There are filters for =, <, >, ≤, ≥ and ≠. Note the asym-

1 The space between n and d is required to separate the lexical tokens.
2 Allowing any expression to be prefixed by a number causes ambiguity, hence the need for an explicit operator.
3. DIFFERENCES FROM ROLL

The basic idea of operations on multisets is unchanged from Roll to Troll, so the changes have mainly been addition of more operators, changes to syntax and new loop structures. Below is a summary of the changes and the reasons for them:

- The dice-operator \( \text{d} \) was in Roll purely a prefix operator, so to roll several identical dice, you needed the \( \# \) operator, i.e., \( 3\#d6 \) instead of \( 3d6 \). Troll added the \( m\{\} \) form to get closer to the familiar Dungeons & Dragons notation.
- Troll added the set-like notation with curly braces, where Roll required building multisets by using the \( @ \) (union) operator. In particular, this has made specification of the empty collection easier, as you can write \( \{ \} \) instead of, for example, \( 0@0 \).
- Local binding in Roll used a \( \text{let-in} \) syntax like in ML or Haskell, but users found the assignment-like syntax easier to read and write, especially when several bindings are nested.
- Filters (comparisons) were prefix operators in Roll, so you would write \( \langle 3 \ x \rangle \) instead of \( 3 > x \). The motivation for the prefix syntax in Roll was to emphasise the asymmetric nature of filters, but users found it confusing.
- Roll had a more powerful loop structure that allowed changes in variables between iterations, but it was too complex for most users. Hence, it was replaced by the simpler \( \text{repeat} \) and \( \text{accumulate} \) loops, and recursive functions were added to handle the more complicated (and much rarer) cases.
- More predefined operators were added. Some were just abbreviations of common cases, such as \( \text{min} \) abbreviating \( \text{least} \ 1 \), while others would be impossible to emulate without using recursive functions. An example of this is \( \text{pick} \), which picks \( n \) elements from a multiset.

As an example, the World of Darkness roll described earlier would in Roll be written as

\[
\text{count } N\# >7 \text{ let } x = d10 \text{ in } \text{repeat if } =10 x \text{ then } d10 \text{ else } 0@0
\]

which is, clearly, less readable.

Nearly all changes have been motivated through discussions with or requests from users of earlier versions. Sometimes to make descriptions easier to write and read and sometimes to make it possible to at all specify a certain dice-roll method.

4. IMPLEMENTATION

Troll is implemented as an interpreter written in Standard ML (specifically, Moscow ML). Two semantics are implemented:

- A random-roll semantics, where the interpreter makes random samples of the described dice-roll.
- A probability semantics, which calculates the probability distribution of the possible outcomes of the described dice-roll.
The random-roll semantics is implemented as a fairly straightforward interpreter using a pseudo-random-number generator seeded by system time, so this will not be detailed further. The implementation of the probability semantics is a bit more interesting, so we will elaborate on this.

If we for the moment ignore loops and recursive functions, a probability distribution for a dice roll is a finite map from outcomes to probabilities, such that the probabilities add up to one. Loops and recursion can make the number of possible outcomes infinite and allow the possibility of non-termination with non-zero probability, so a finite map is insufficient. We will, nevertheless, use finite maps and deal with the infinity issue later.

We will write a finite map as a set of pairs of values and probabilities. For example, the distribution for \texttt{sum 2d2} is:

\{(2, 0.25), (3, 0.5), (4, 0.25)\}

There are, basically, two ways in which we can calculate a finite probability map for a dice-roll definition:  

1. We can from each subexpression produce a finite map for its possible outcomes and combine these to find a finite map for the outcomes of the full expression.

2. We can use Prolog-style backtracking to obtain all possible outcomes and deal with the infinity issue later.

We can call the first method \textit{enumeration in space} and the second \textit{enumeration in time}. They have different advantages and disadvantages:

- **Enumeration in space needs to enumerate all intermediate values at the same time, so if there are more intermediate values than final values, you can use very large amounts of memory. An example is \texttt{sum nd10}, where there are O(n^3) possible values of nd10 but only O(n) possible values for the sum.** Hence, enumeration in time will use only O(n) space, while enumeration in space will use O(n^3) space.

- **Enumeration in time needs only keep track of one value at any given time (except at the top-level count), so you don’t need very much space.**

- **Because enumeration in time looks at intermediate values one at a time, it can not recognize that it has seen a value before and will, hence, often repeat calculations that it has already done. Enumeration in space can combine identical values in the finite map by adding up their probabilities and, hence, avoid doing further calculation twice.** For example, while nd10 has O(n^3) possible values, enumeration by backtracking has to look at 10^9 combinations. To find the distribution for \texttt{sum nd10}, enumeration in time has to look at 10^6 multisets of n numbers and add these up using 9 additions for each. Enumeration in space will combine values for nd10 so it only needs to add up O(n^9) multisets.

Though space costs more than time on modern computers, reduction from exponential to polynomial time is worth an polynomial increase in space.

\(3\)To be precise, nd10 has \(\left( \frac{n+9}{9} \right)\) possible outcomes.

Even so, enumerating O(n^3) multisets to find the distribution for \texttt{sum nd10} requires a lot of time and space. Fortunately, we can do better by the following observation:

Since \(\text{sum}(A \cup B) = \text{sum}(A) + \text{sum}(B)\), we can find the distribution for \texttt{sum nd10} by first finding the distributions for \texttt{sum (n-1)d10} and \texttt{sum d10} and combine these into a distribution for \texttt{sum nd10}. If we apply this recursively, we never need to store a distribution with more than O(n) values, since there are only O(n) possible outcomes for \texttt{sum nd10} where \(m < n\).

To exploit such algebraic properties, Troll uses a non-normalised representation for distributions described by the following recursive data-type definition:

\[
D \equiv M! \ + \ D \cup D \ + \ D \cup p D \ + \ 2 \times D
\]

where \(M\) is a multiset of numbers and \(0 < p < 1\). \(M!\) denotes the distribution with only one possible outcome, which is \(M\), \(d_1 \cup d_2\) combines the outcomes of two distributions by union, \(d_1 \cup p d_2\) chooses between the outcomes of two distributions with probability \(p\) of choosing from the first, and \(2 \times d\) is an abbreviation of \(d \cup d\).

We can translate this representation into finite maps by the function \(F\) below:

\[
F(M!) = \{(M, 1)\}
\]

\[
F(d_1 \cup d_2) = \{(M_1 \cup M_2, pq) \mid (M_1, p) \in F(d_1), (M_2, q) \in F(d_2)\}
\]

\[
F(d_1 \cup p d_2) = \{(M, pq) \mid (M, q) \in F(d_1) \cup \{(M, (1-p)q) \mid (M, q) \in F(d_2)\} \}
\]

\[
F(2 \times d) = \{(M_1 \cup M_2, pq) \mid (M_1, p) \in F(d), (M_2, q) \in F(d)\}
\]

By operating on this representation, we can exploit two kinds of algebraic properties of functions on multisets:

- **A function \(f\) is linear if \(f(A \cup B) = f(A) \cup f(B)\).**

- **A function \(f\) is homeomorphic if there exists an operator \(\oplus\) such that \(f(A \oplus B) = f(A) \oplus f(B)\).**

Examples of linear functions include filters like \(\ll\). We can lift a linear function \(f\) to distributions in the following way:

\[
f(M!) = f(M!)
\]

\[
f(d_1 \cup d_2) = f(d_1) \cup f(d_2)
\]

\[
f(d_1 \cup p d_2) = f(d_1) \cup f(p d_2)
\]

\[
f(2 \times d) = 2 \times f(d)
\]

Examples of homeomorphic functions include \(\text{sum}\) (\(\oplus\) is +), \text{count} (\(\oplus\) is +) and \text{min} (\(\oplus\) is \(\min\)). We can lift a homeomorphic function \(f\) to distributions in the following way:

\[
f(M!) = f(M!)
\]

\[
f(d_1 \cup d_2) = f(d_1) \oplus f(d_2)
\]

\[
f(d_1 \cup p d_2) = f(d_1) \oplus f(p d_2)
\]

\[
f(2 \times d) = \oplus^2 f(d)
\]

\[
M! \oplus N! = (M \oplus N)!
\]

\[
(d_1 \oplus d_2) \oplus d_3 = (d_1 \oplus d_3) \oplus (d_2 \oplus d_3)
\]

\[
d_1 \oplus (d_2 \oplus d_3) = (d_1 \oplus d_2) \oplus d_3
\]

\[
\oplus^2 M! = (M \oplus M)!
\]

\[
\oplus^2 (d_1 \cup p d_2) = (\oplus^2 d_1) \cup \frac{(\oplus^2 d_2) \cup (\oplus^2 d_2)}{1 - p^2}
\]

\[
\oplus^2 (d_1 \cup p d_2) = (\oplus^2 d_1) \cup \frac{(\oplus^2 d_2) \cup (\oplus^2 d_2)}{1 - p^2}
\]
where $\oplus$ is the operator for the homeomorphism $f$, $\otimes$ is $\oplus$ lifted to union-free distributions and $\otimes^+d$ is an optimized version of $d\otimes d$.

### 4.1 Local bindings

If we locally bind a value to a variable, as in $x := d6; x+x$, the two occurrences of $x$ after the semicolon must always refer to the same value. Hence, in the expression $x+x$, the distribution for $x$ must have only one possible outcome. So the local binding must normalise the distribution for $x$ to a finite map and then evaluate $x+x$ for each possible value and combine the results to a new finite map.

By normalising, we lose all of the optimisations of using a non-normalised representation, so local binding is one of the most costly operations in Troll.

We represent normalised finite maps as a special case of the non-normalised representation where there are no union nodes and where the left operand to a choice node is always the non-normalised representation where there are no union operations, so local binding is one of the most costly operations in Troll.

### 4.2 Loops

The first observation is that since all iterations evaluate the same expression and the last such evaluation provides the result, the outcomes of a loop of the form

```
repeat x := e until c
```

is a subset of the outcomes of $e$.

The way we handle loops in Troll is to first calculate the distribution $d$ for $e$ and then rewrite $d$ into a form $d_1|_p d_2$, where all outcomes of $d_1$ fulfill the condition $c$ and none of those of $d_2$ do. It is now clear that the distribution for $x := e$ until $c$ is $d_1$: Repetition is done until we have a result in $d_1$, regardless of how unlikely this is. There is a possibility $p = 0$, i.e., that none of the outcomes of $e$ fulfill $c$. It would be possible to include nontermination as a possible value in distributions, but since dice rolls are intended to terminate, we instead report an error whenever there is a positive chance of nontermination.

An accumulating loop of the form

```
accumulate x := e until c
```

can have an infinite number of possible outcomes. If we, like above, rewrite the distribution for $e$ into the form $d_1|_p d_2$, we find that the distribution $d'$ for the loop can be defined by the equation

$$d' = d_1|_p (d_2 \cup d')$$

This will not have a finite solution unless $p = 1$ or $d_2 = \{\}$. Instead of trying to work with infinite maps, we have chosen to approximate by unfolding the above equation a finite (but user-definable) number of times and then replacing the remaining recursive reference to $d'$ by $d_1$. If rerolls have probability less than 1, we can get arbitrarily good approximations by increasing the unroll depth.

We are now left with the problem of rewriting $d$ to $d_1|_p d_2$ given the condition $c$. We note that the loop introduces a local binding, so we start by normalising $d$. We then find $d_1|_p d_2$ by the following function:

| $C(M!)$ | $M!|_p M!$ |
|---------|------------|
| $c_M$   | 1 - $E(c_M)$ |
| $p$     | $E(d|_p d')$ |
| $d_1|_p d_2$ | $d_1|_p d_2'$ |
| $d_1|_p d_2'$ | $C(d_1)$ |
| $d_1|_p d_2'$ | $C(d')$ |
| $p_1$   | $pq + (1-p)r$ |
| $p_2$   | $pq/p_1$ |
| $p_3$   | $p(1-q)/(1-p_1)$ |

The $M!|_p M!$ in the first line may seem a bit curious, as it is equivalent to $M!$, but since $p$ is significant for later calculations, we write the distribution in this redundant way. If there are several possible values for $x$, i.e., if the normalised distribution contains a choice, we calculate the split for each possible value and combine the results.

$E(d)$ is the probability that an outcome of $d$ is the empty multiset. Since conditions are considered true when they evaluate to non-empty multisets, the probability of a condition being true is 1 minus the probability of it being empty.

### 4.3 Other optimisations

In most places where distributions are built, some local simplifications at the top-level of the tree-structure are attempted. An incomplete list of these is shown below.

| $d|_p d$   | $d_1|_p d_2$   | $d_1|_p d_2'$   |
|------------|----------------|-----------------|
| $d_1|_p d_2$ | $d_1|_p d_2'$   | $d_1|_p d_2'$   |
| $d_1|_p d_2'$ | $d_1|_p d_2'$   | $d_1|_p d_2'$   |
| $d_1|_p (d_1|_q d_2)$ | $d_1|_p d_2'$   | $d_1|_p d_2'$   |
| $\{\}|_p d$ | $\{\}|_p d$   | $\{\}|_p d$   |
| $M! \cup N!$ | $(M \cup N)!$ |

These add a small overhead to construction of trees, but can sometimes reduce their size dramatically.

### 5. ASSESSMENT

So, how well does Troll work?

#### 5.1 The language

While Troll is considerably easier for non-programmers and programmers alike to use than Roll, people with no programming experience at all usually find it hard to write definitions that involve conditionals or loops, but expressions like `sum largest 3 4d6` or `count 7<5d10` are not usually any problem. People with a minimum of programming experience (such as experience from writing formulae in spreadsheets) can usually write definitions using a single loop or conditional and more experienced users can use all of the language.

Usually, people can read and understand definitions that are more complex than they can write.

While a number of game designers around the world use Troll to calculate probabilities, the notation has not been
adopted in any game rules texts. Any one game will usually
only use one or two different dice-roll methods, so it is easier
for the writers to use a specialised notation or just plain
English. Nor has any Internet dice-server used Troll to allow
users to describe rolls that are not pre-programmed. So,
overall, the success of Troll has almost exclusively been in
probability calculation, where there (to my knowledge) are
no other similar tools.

5.2 The implementation

Due to the optimisations enabled by the non-normalised
representation, calculating the probability distribution of
most simple definitions is very fast. For example, calculating
the distribution for \texttt{sum 50d10} takes about 0.1 second on my
fairly old machine\footnote{3.2GHz Pentium 4, 1.5GB RAM} and the calculation for \texttt{count 7<100d10}
takes less than 0.01 second.

But when rolls combine a large number of dice and oper-
ations that do not distribute well over the non-normalised
representation, calculations can take very long and use enor-
rious amounts of memory. This can even happen for dice-
roll systems used in actual games. For example, the game
“Legend of Five Rings” [18] uses a roll mechanism that can
be described in Troll as

\[
\text{sum (largest M N#(sum accumulate x := d10 until x<10))}
\]

where \(M\) and \(N\) depend on the situation. With \(M = 3, N = 5\)
and the maximum number of iterations for \texttt{accumulate} set
to 5, Troll takes nearly 500 seconds to calculate the result,
and it gets much worse if any of the numbers increase.

If exact calculation of probabilities takes too long, the
random-roll semantics of Troll can be used to generate a
large number of samples which can be used to calculate
statistics that approximate the probabilities.

6. RELATED WORK

Apart from the notation originated in Dungeons & Drag-
ons [3], most examples of notation for dice-roll are used only
in games from a single publisher. Wikipedia [16] lists a few
examples of those. Besides Roll [7] and Troll, the only other
attempt at defining a universal dice-roll notation that I know
of is in a Usenet post from 1992 [14]. There are many simi-
larities between this and Troll. Numbers are kept separate
until explicitly summed or otherwise operated on and there
are clear equivalences to the Troll operations \texttt{sum, d, #, least}
and \texttt{largest} (but not to the more complex Troll features).
A partial implementation of the language was implemented
in a dice-roll calculator [15].

There are many examples of extending traditional lan-
guages with probabilistic choice operators, e.g., [9, 2, 12],
but in the main these do not allow calculation of probabili-
ties, only sampling at runtime.

Other languages are designed for calculating probabili-
ties [10, 5, 8, 11]. None of these are specialised for defining
dice-rolls, but some similarities to Troll exist. For exam-
ple, the stochastic lambda calculus [11], like Troll, can be
instantiated to both a sampling and probability calculation.
The authors note that calculating probabilities for product
spaces (which are similar to unions) can take very long time
and discuss translating expressions into \textit{measure terms} that
keep the parts of a product space separate as long as pos-
sible. This has some similarities to using a non-normalised
form, but the measure terms are more complex (and po-
tentially more powerful) than the representation used in
Troll. The main probabilistic construct in the stochastic
lambda calculus is \texttt{choose p e1 e2}, which is equivalent to
the \(d1 | p d2\) form in the unnormalised representation in Troll.

The predecessor of Troll, Roll is described in a paper [7]
that includes formal semantics for both sampling and proba-
bility calculation. An implementation using an unnormalised
representation similar to the one described in this paper is
described, but not all the optimisations described above
were applied to Roll.

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