A Simple Parallel Implementation of Interaction Nets in Haskell

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Due to their “inherent parallelism”, interaction nets have since their introduction been considered as an attractive implementation mechanism for functional programming. We show that a simple highly-concurrent implementation in Haskell can achieve promising speed-ups on multiple cores.

1 Introduction

The interaction nets introduced by Lafont [Laf90] can be considered as a variant of term graphs, and therewith as a kind of graphs used as representation of terms. Interaction nets are equipped with an “inherently parallel” local and confluent reduction mechanism that makes them an, at least conceptually, attractive target for (functional) programming language implementation. However, to date there have been only limited experiments with parallel implementations of interaction nets, and no easily-usable parallel implementation is publicly available. In addition, the nature of the parallelism of interaction net reduction is in general rather fine-grained, so that the question of distribution strategies arises naturally.

In this paper, we report on an experiment that bypasses the question of distribution strategies, and instead investigates whether a fine-grained threading mechanism with parallel execution on shared-memory multi-core systems, as provided by the run-time system of the Glasgow Haskell Compiler (GHC), can already realise the potential of parallelisation offered by interaction nets. Our implementation is publicly available (at http://www.cas.mcmaster.ca/~kahl/Haskell/HINet/) and accepts a slightly restricted version of the Inets file format, enabling further experiments also by other interaction net researchers. In the benchmarking section, we provide a lot of data, and also discuss the potential pitfalls of benchmarking Haskell programs with large heap requirements, in order to aid potential users of our system to avoid these pitfalls.

1.1 From Term Graphs via Jungles and Code Graphs to Interaction Nets

We now give an introduction to interaction nets that puts them into the context of different term graph representations. We do this for two reasons: First, to make interaction nets more accessible for readers interested in functional programming language implementation, who may already be familiar with graph reduction, but might find the principal-port orientation of most of the interaction net literature rather obscure, and second, to give a clear understanding of polarities, which have almost disappeared from the interaction net literature.

Conventional term graphs (see e.g. [KKSv93]) are node-labelled directed graphs, where each node has a sequence of outgoing edge the length of which is determined (or sometimes part of) the label. Node labels of these term graphs correspond to function symbols in terms; variables do not need labels: Different variable nodes (labelled “V” below) represent different variables.

The “jungle” approach of Hoffmann and Plump [HP91] moves the function symbols into hyperedges, with a sequence of “argument tentacles” (or “input tentacles”) extending to argument nodes, and (normally) exactly one “result tentacle” (or “output tentacle”) extending to the hyperedge’s result node (or
output node). In both approaches, there is no restriction on the number of edges (resp. input tentacles) incoming into each node; multiple incoming edges implement sharing (and zero incoming edges into a non-root node implement (uncollected) “garbage”, where in term graph and jungle rewriting, garbage collection is typically implicit).

The drawing above shows a conventional term graph, a jungle, and an interaction net each representing the term \((2 + x) \ast x + (2 + x) \ast y\) with the same degree of sharing. In all three drawings, the sequence of the outgoing or incoming edges, respectively tentacles, or ports, of each node or hyperedge is part of the structure, but is, as customary, not made more explicit.

Interaction nets are different from jungles in several ways. First of all, a different terminology is used: Instead of “hyperedge”, the terms “node” or “agent” are used, the nodes of jungles turn into “connections” and the tentacle labels and directions turn into “ports”. In interaction nets, connections must be incident with exactly one or two ports; those incident with only one port make up the interface of the net. Because of this, sharing and garbage must be made explicit via duplicator (“\(\nabla\)”) and terminator (“\(!\)”) nodes. Each interaction net node label determines one principal port for its nodes. We draw principal ports as filled-in circles attached to the rectangular nodes, while auxiliary ports are hollow. Interaction net rules only replace pairs of nodes connected via their principal ports.

The directions of edges in termgraphs, and of tentacles in jungles, are motivated by denotational semantics; the corresponding directions of connections in interaction nets were introduced under the name polarities by Lafont [Laf90], but are omitted in a large part of the interaction net literature, where interaction nets are drawn with undirected connections. Instead, the operationally motivated direction of nodes (“actors”) from auxiliary ports to the principal port is typically emphasised. We follow Lafont [Laf90] to distinguish output ports (with positive polarity) and input ports (negative polarity), and draw connections as directed arrows from output to input ports. Note that besides Lafont [Laf90], most of the interaction net literature does not draw nets in a way that easily corresponds to a jungle reading.

Whereas jungle hyperedges have only one output tentacle, the duplicator (\(\nabla\)) nodes of the interaction net above have two output ports — a feature that also occurs in the code graphs of [KAC06, AK09]. We illustrate this with a second example; the term \((2/x) \ast y + (2\%x) \ast y\) represented with sharing as a term graph has two variable nodes corresponding to \(x\) and \(y\); represented as jungle these turn into two input nodes.
In code graphs, the sequence of these input nodes is explicitly visualised via triangular tags with arrows towards the input nodes; code graphs also have a sequence of output nodes visualised via triangular tags with arrows from the output nodes. Code graph hyperedges also have as interface a sequence of input nodes (as in jungles) and a sequence of output nodes, which in contrast to jungles is not constrained to contain exactly one element. For the sake of an example, we can therefore use a two-output operation “divMod” to obtain a code graph that uses a single operation to produce the same result as the two separate operations / and % in the term and jungle above. (The sequences of input and output nodes of hyperedges are still indicated implicitly via the graphical arrangement.)

Since code graphs allow multi-output nodes, duplicators (“∇”) do not need to be given any special status, and interaction net languages can be understood as code graph languages without node-based sharing (and without “garbage”), which allows us to replace the code graph nodes with their single incoming and outgoing tentacles with simple connections. Input and output nodes of code graphs turn into input and output ports of interaction nets — these are the ports of negative, respectively positive polarity that have no connection attached to them. As for code graphs, we will assume the input and output ports to be organised into two sequences, and tag them using the same triangles.

### 1.2 Interaction Net Rules and Reduction

Application of rules is defined as subnet replacement, where the input and output ports of the rule sides may map to arbitrary ports in the application net. Due to the constraints on the left-hand sides of rules, the resulting reduction has no critical pairs; it is therefore confluent and has a deterministic normalisation relation. Since left-hand sides match only to subnets induced by two nodes connected via their principal ports, reduction exhibits extreme locality, and is frequently considered as “inherently parallel”.

Below, we show rules for addition and multiplication of natural numbers built up from the constructors for zero (“0”) and successor (“S”). The first multiplication rule, “mult 0 n = 0”, turns n into “garbage” by attaching a terminator (“!”) node; the second multiplication rule “duplicates” n for use both by the addition and by the recursive call.
The reader may notice that the multiplication rules provided above always perform a “superfluous” last addition to zero if the first factor is non-zero. One might consider the following starting point instead:

\[
\begin{align*}
\text{mult } 0 \ n &= 0 \\
\text{mult } (S \ 0) \ n &= n \\
\text{mult } (S \ m) \ n &= \text{add } n \ (\text{mult } m \ n)
\end{align*}
\]

However, the “deep pattern matching” here cannot be implemented directly by conventional interaction net reduction; the rules drawn above to the right are however allowed in the extension proposed by Hassan et al. [HJS09] which translates them into conventional interaction net rules by adding an auxiliary function:

\[
\begin{align*}
\text{mult } 0 \ n &= 0 \\
\text{mult } (S \ m) \ n &= \text{multAux } m \ n \\
\text{multAux } 0 \ n &= n \\
\text{multAux } (S \ m) \ n &= \text{add } n \ (\text{multAux } m \ n)
\end{align*}
\]

Such encoding issues are not relevant to the current study, which considers interaction nets as an execution model, rather than as a programming language. Compilation to interaction net rules is a separate topic, and has been studied for example by H. Cirstea and others [CFF+07] using the \( \rho \)-calculus as intermediate language.

1.3 Related Work

Pedicini and Quaglia [PQ07] describe PELCR, a distributed parallel environment for optimal \( \lambda \)-calculus reduction, which uses a specialised fixed interaction net language and implements sophisticated distribution strategies. (I found no trace of this being or having been publicly available.) Besides such specialised systems, we are aware of only a small number of parallel implementations of interaction nets, in particular [BP97, Pin01, Jir14]. Of all these, only the last seems to be (still) available; it is an experimental GPU implementation that requires new rules to be implemented manually in C/CUDA at a very low level.

A general interaction net implementation that is still available is part of the Inets project of Mackie et al. [HMS09, HJ12]. This it is a compiler for the interaction net definition language I\( \text{nets} \), which is considered as a programming language; the compiler is implemented in Java, and compiles via C to non-parallel executables. While I\( \text{nets} \) implements nets as pointer structures, the (apparently unavailable) successor system “Light” [HMS10], as well as the systems of Pinto [Pin01] and Jiresch [Jir14] are based on a term representation of interaction nets (based on the fact already pointed out by Lafont [Laf90] that “well-behaved” fully reduced nets always can be represented via pairs of terms with common variables and further constraints). Lippi’s implementation called “\( \text{in}^2 \)” [Lip02] was apparently close in spirit, but not directly based on terms.

Other available implementations are geared more towards graphical interaction directly with interaction nets (and also don’t support parallel execution), including de Falco’s “Interaction Nets Laboratory” [Fal06], the “interaction net IDE” INblobs of Almeida et al. [APV08], and the graph rewriting system IDE “PORGY” [AFK+11] which can also be used for interaction nets. By emphasising visualisation of net transformations, these tools by design cannot target efficient parallel implementation.
1.4 Contribution and Overview

We present a design for highly concurrent interaction net implementations that is at the same time surprisingly simple and very close to the graph understanding of the interaction net definition. The parallel implementation of concurrency in the Glasgow Haskell Compiler (GHC) is a good fit for this kind of design; our implementation obtains satisfactory speed-ups even for simple examples.

While most current non-graphical implementations of interaction nets are based on a term-based calculus, we explain our more direct approach in Sect. 2. The actual (literate) Haskell source code of the kernel of our implementation is then presented in Sect. 3 — the full source code is available on-line at http://www.cas.mcmaster.ca/~kahl/Haskell/HINet/. In Sect. 4 we summarise our implementation of a language similar to that of Inets [HJ12]. Measurements and relevant observations are in Sect. 5.

2 Implementation Design

Our implementation essentially follows the main ideas of Banach and Papadopoulos [BP97]:

- Two-way connections, which easily introduce opportunities for deadlock and race conditions, can be avoided by using polarities to direct the connections between ports (which, in a large part of the literature, are treated as undirected, and implemented as two-way connections).

- These directed connections hold mutable state.

- The connection with the principal port of a constructor does not need to be known to the constructor node if the connection state refers to the node.

The following main decisions then determine most of our implementation details:

- Connections (drawn below as thick circles) are initially “empty”, and each node has references to the connections attached to its auxiliary ports.

- Attaching the principal port of a constructor to a connection deposits a reference to the constructor node in the connection (which is then “full”). (This reference is drawn below with a thick arrow with a bullet tail.)

- Attaching the principal port of a function to a connection starts a concurrent thread that waits for a constructor reference in that connection, and if/when it finds one, starts the corresponding rule application. (This is drawn below with an even thicker arrow ending inside the connection.)

The following shows a net fragment first in the same style as the previous example, and to the right with implementation details added.
3 Implementation in Concurrent Haskell

We implement connections using the Concurrent Haskell synchronisation primitive MVar, which can be created empty; putMVar waits for empty state to fill, and takeMVar waits for full state to empty \cite{PJGF96}. The GHC version of Concurrent Haskell has an extremely light-weight thread implementation that makes it feasible to create millions of threads; we therefore directly create new threads for functions as mentioned above, and even smaller threads for short-circuiting two interface ports that are directly connected by rule applications: These threads only wait for a constructor on the originally negative port of the LHS, and copy it to the positive side.

The run-time implementation of nets, based on MVars, is introduced in Sect. 3.2. For the static representation of rules, our implementation uses a non mutable datatype NetDescription to represent right-hand sides (RHSs) of reduction rules; these are introduced in Sect. 3.3. At run-time, these NetDescriptions are instantiated into new parts of the mutable run-time net, as fully defined in Sect. 3.4 following the principles outlined in Sect. 2.

3.1 Polarity

Lafont \cite{Laf90} and Banach and Papadopoulos \cite{BP97} use typed connections in their interaction nets, where the two ports incident in a connection have the same type, but different polarity. Since we design our interaction net implementation as a run-time system, types are currently not important, and will be assumed to have been taken care of before net generation. Polarity, however, drives several run-time decisions; for the sake of readability, we define a special-purpose data-type for it (and let Haskell’s “deriving” mechanism provide us with the default implementation of equality and ordering tests, and of conversion to strings):

```haskell
data Polarity = Neg | Pos
  deriving (Eq, Ord, Show)
  opposite :: Polarity -> Polarity
  opposite Neg = Pos
  opposite Pos = Neg
```

We will follow Lafont’s convention of letting “constructors” have positive polarity, and “functions” negative polarity.

3.2 Mutable Net Representation

A connection between two ports is implemented as a single MVar that is either empty, or contains the constructor node for which the connection is at the principal port. (To allow different node label types to be used, we use the type variable nLab throughout.)

```haskell
type Conn nLab = MVar (Node nLab)
```

For an auxiliary port of a node, besides its connection we also record the port’s polarity to make it available efficiently at run-time. (In Haskell, data constructors for simple record types habitually are given the same name as the type constructor; the fields pol and conn here are declared strict using “!”, and the “UNPACK” pragma declares an “unpacking” optimisation as desired to the compiler.)

```haskell
data Port nLab = Port
  { pol :: ! Polarity
```
We introduce the type synonym `Ports` to abbreviate the type of port arrays.

```haskell
type Ports nLab = Vector (Port nLab)
```

Given a port `p`, the port at the other end of its connection is obtained as `opPort p` by flipping the polarity:

```haskell
opPort :: Port nLab → Port nLab
opPort p = p { pol = opposite $ pol p }
```

A node contains a label, and the array of its non-principal ports. We do not include the principal port in `ports` since

- the principal port of a constructor is connected to the MVar pointing back to the constructor, and
- the principal port of a function is connected to the MVar the function’s thread is waiting on.

```haskell
data Node nLab = Node
    { label :: nLab
    , ports :: Ports nLab
    }
```

### 3.3 Net Descriptions

Whereas in Sect. 3.2, we introduced types for nets considered as run-time states, here we introduce *net description* for static representation of, in particular, rule right-hand sides.

The following types are dictated by our current choice of array implementation (Data.Vector from the vector package, for efficiency), but aliased for readability:

```haskell
type PI = Int -- "port index"

type NI = Int -- "node index"
```

The port index type `PI` will be used also in actual nets, while the node index type `NI` is needed only for right-hand side nodes in descriptions and during creation. We arbitrarily call the two nodes engaged in an interaction “source” and “target”; the “source” interface consists of the auxiliary ports of the node with the “function” label with negative principal port, and the “target” interface consists of the auxiliary ports of the “constructor” node with positive principal port. The following data type serves to identify all ports in a rule’s right-hand side (the “!” specifies strict constructor argument positions for efficiency):

```haskell
data PortTargetDescription
    = SourcePort !PI
    | InternalPort !NI !PI -- node, port
    | TargetPort !PI deriving (Eq, Ord, Show)
```

Therefore, each RHS node is described by its label and by the connections of *all* its ports:

```haskell
data NodeDescription nLab = NodeDescription
    { nLab :: : ! nLab
    , portDescriptions :: {-# UNPACK #-} ! (Vector PortTargetDescription) }
```
A NetDescription is intended as a description of the RHS of interaction rules:

```haskell
data NetDescription nLab = NetDescription
  { source :: {# UNPACK #} ! (Vector PortTargetDescription)
  , target :: {# UNPACK #} ! (Vector PortTargetDescription)
  , nodes :: {# UNPACK #} ! (Vector (NodeDescription nLab))
}
```

A language for interaction nets consists of a type of node labels together with arity and polarity information defining all ports for each node label, and for any “function” node label \( f \) and any “constructor” node label \( c \) that can occur as “argument” to \( f \) a rule, specified by a right-hand side \( \text{ruleRHS} f c \), which needs to be a net description having a source compatible with the auxiliary ports of \( f \), and a target compatible with the auxiliary ports of \( c \).

```haskell
data INetLang nLab = INetLang
  { polarity :: ! (nLab → Vector Polarity)
  , ruleRHS :: ! (nLab → nLab → NetDescription nLab)
  }
```

### 3.4 Interaction Net Reduction

The main purpose of the function replaceNet is to implement the instantiation part of the rule application step. It is a separate function because it also serves the secondary purpose of constructing the start net.

The function replaceNet takes as arguments a NetDescription (defined in Sect. 3.3) for the rule’s RHS, and arrays \( \text{src} \) and \( \text{trg} \) containing the non-principal connections of the two nodes of the image of rule’s LHS in the mutable net representation (Sect. 3.2) of the run-time state.

The \( \text{mdo} \) is a “recursive do” as introduced by [EL02], and the use here essentially corresponds to the imperative programming pattern of allocating an array of uninitialised cells, and creating references to the array cells possibly before initialising them. (Functions prefix with “V.” operate on Vectors.)

```haskell
replaceNet :: forall nLab ◦ INetLang nLab → NetDescription nLab
  → Ports nLab → Ports nLab → IO ()
replaceNet lang descr src trg = mdo
  nps ← let mkNode (NodeDescription lab pds) = do
    ps ← V.zipWithM mkPort (polarity lang lab) pds
    return (Node { label = lab, ports = V.tail ps }
    , V.head ps)
  where mkPort Pos (InternalPort _) = fmap (Port Pos) newEmptyMVar
    mkPort Pos ptd = return (portTarget ptd)
in V.mapM mkNode (nodes descr)
```

The first step above creates descr image nodes, taking over interface ports from src and trg, creating new internal connections at positive ports, and lazily connecting negative ports with internal connections located via the function portTarget defined below.

Note that the prose explanations here are interspersed within the scope of the mdo above, since all code before the definition of reduce below remains indented below the mdo.

```haskell
let portTarget :: PortTargetDescription → Port nLab
  portTarget (SourcePort i) = atErr "portTarget: SourcePort S" src (pred i)
```
portTarget (TargetPort i) = atErr "portTarget: TargetPort S" trg (pred i)
portTarget (InternalPort n i) = let e = "portTarget: InternalPort "
   (n', pp) = atErr e nps n
   in opPort (if i ≡ 0 then pp else atErr (e ++ shows n " S") (ports n') (pred i))

We traverse the newly created nodes and “connect” their principal ports.

let doNode (n@(Node lab prts), Port pl c) = case pl of
   Neg → forkIO (reduce lang (ruleRHS lang lab) c prts) >>= return ()
   Pos → putMVar c n
   in V.mapM_ doNode nps

For source and target ports, we only need to take care of short-circuits:

let dolfasePort (Port Pos c) ptd = return () -- will be done from the other side if necessary
dolfasePort (Port Neg c) ptd = let -- original port of the LHS node
   Port _ pl' c' = portTarget ptd
   in if c ≡ c' then return () -- empty cycle
      else case ptd of
         InternalPort n i' → return () -- already dealt with
         _ → do forkIO (moveMVar c c')
             return ()
   in do V.zipWithM_ dolfasePort src $ source descr
        V.zipWithM_ dolfasePort trg $ target descr

Whenever a function node is created, i.e., a node with positive principal port, a reduce thread is started (via forkIO). This thread waits on the connection (pconn) between the principal ports of the rule until this contains the constructor node (the principal port of which has positive polarity). The array src contains the auxiliary ports of the function node (the principal port of which has negative polarity).

reduce :: INetLang nLab → (nLab → NetDescription nLab) → Conn nLab → Ports nLab → IO ()
reduce lang rules pconn src = do
   Node clab trg ← takeMVar pconn
   replaceNet lang (rules clab) src trg

4 Reading .inet Files

The Inets project led by Ian Mackie has implemented the only publicly available general implementation of interaction nets, the compiler [HJ12] for the interaction net programming language “Inets”. This language was introduced by Mackie [Mac05], with the core of the Inets implementation described in [HMS09].

We implemented a front-end to our interaction net reduction system for the core sublanguage of Inets, leaving out in particular the extension of nested pattern matching described in [HMS10], and generic rules and variadic agents.

Since our system depends on polarity for its directed implementation of connections, but Inets has no concept of polarity, we adopted the convention that the first-mentioned agent of each rule has negative principal port (that is, is considered as a function), and the second agent has positive principal port (constructor). This convention is adopted in most of the Inets examples anyways; only two rules in fibonacci.inet had been written the other way around. From this starting point we attempt to deduce
the polarities of all other ports; for the examples accessible to us so far, we only needed to add a single additional heuristic: A function for which all other ports except one are known to have negative polarity is assumed to have positive polarity on the last port. (Unfortunately the $\lambda$-calculus evaluator yale.inet [Mac98] is defined in a way that does not allow a consistent assignment of polarities.)

Inets supports “parameters”, that is, agent attributes of the primitive types int, bool, float, char, and String. The description in [HMS09] suggests that only a single parameter is allowed per agent; our implementation allows arbitrary numbers, but expects the number and types of attributes to be determined by the agent label. We also interpret type int as Haskell’s arbitrary-precision Integer type. Our current interpreting implementation uses a parameterised agent label type:

```haskell
data NLab arg = NLab { nLabName :: Name, nLabAttrs :: [arg] }
```

When reading a .inet file, the nets on the rule RHSs are translated into NetDescription (NLab Expression) and stored in a finite map for lookup by the rule LHS agent label pair; in the run-time net, agent labels of type NLab Value are used, and the variable bindings induced by the attributes of the interacting nodes are used at the time of rule application to evaluate the expressions in the RHSs (and the condition expressions for the conditional structure of Inets RHSs).

Inets modules can contain global variables, which are used in the examples to implement reduction counts etc.; since in a parallel implementation such global variables would require synchronisation (and thus would destroy the independence of parallel reduction), we did not implement any feature related to global variables.

## 5 Benchmarks

For our first examples, we use a cascading recursion for calculating Fibonacci numbers, and the Ackermann function, both computing with unary natural numbers constructed from zero $Z$ and the unary successor constructor $S$:

```haskell
fib 0 = 0
fib (S n) = fibAux n
fibAux 0 = 1
fibAux (S n) = fib n + fibAux n
```

```haskell
ack 0 n = S n
ack (S m) n = ackAux m n
ackAux m 0 = ack m 1
ackAux m (S n) = ack (ack (S m) n)
```

These rules were directly encoded using NetDescriptions (see Sect. 3.3); we will refer to these implementations now as fibND and ackND.

We timed the actual code of Sect. 3 on a six-core 2.8GHz Phenom 2 with 16GB main memory; our implementation achieved the timings in Table 1 where the GHC run-time system is instructed by “−Nk” to use $k$ cores for parallel processing. The user-space time of a Haskell process is divided into “mutation” time and garbage collection time. The run-time system can be made to report these times and further information; in Tables 1 and 2 we include, after the elapsed time for each process (which is the “real” time as reported by “time” BASH built-in), the “allocation rate”, which measures how many megabytes are allocated on the Haskell heap per second of mutation time, and the “productivity”, which is the result of dividing the mutation time by the elapsed time. For example, a productivity of 240% for a three-core (“−N3”) run means that each core spent on average 20% of its time on garbage collection, since $240\% + 3 \times 20\% = 300\%$. The last column in each of the groups for “−N2” to “−N6” contains the speedup over single-core execution.

By default, the GHC run-time system starts execution with a small heap and grows it by relatively small increments on demand; we indicate use of this this default setting by “dft.” in the third column.
Wolfram Kahl

43

("heap"). Where a size is specified in this column, this size was given to the run-time system as fixed heap size (with options -H and -M).

| expr   | result | time (s) | allocation rate (MB per mutation second) | productivity (% of elapsed) | speedup |
|--------|--------|----------|------------------------------------------|-----------------------------|---------|
|        |        | -N1      | -N2                                      | -N3                         | -N4     | -N5     | -N6     |
| ACKND 3.6 | 509    | dft      | 1.078 1169 49 0.630 1189 118 1.74 | 0.483 952 192 2.23 | 0.431 779 264 2.50 | 0.427 611 340 2.52 | 0.426 508 411 2.53 |
|        | 509    | 2M       | 1.004 1716 51 0.630 1188 117 1.59 | 0.489 960 189 2.05 | 0.452 738 266 2.22 | 0.411 647 333 2.44 | 0.421 516 409 2.38 |
|        | 509    | 3M       | 0.800 1695 65 0.586 1196 130 1.44 | 0.478 960 193 1.67 | 0.441 741 258 1.80 | 0.459 632 333 2.79 | 0.429 509 405 1.86 |
|        | 509    | 4M       | 0.648 1678 76 0.504 1205 146 1.38 | 0.444 842 212 1.56 | 0.433 747 274 1.60 | 0.405 646 339 1.71 | 0.425 512 407 1.63 |
|        | 509    | 5M       | 0.652 1652 82 0.475 1944 156 1.37 | 0.415 948 225 1.57 | 0.404 751 293 1.61 | 0.385 652 354 1.69 | 0.422 510 413 1.55 |
|        | 509    | 6M       | 0.647 1664 85.3 0.462 118 163 1.40 | 0.400 945 235 1.62 | 0.397 745 308 1.67 | 0.375 646 367 1.73 | 0.395 522 431 1.64 |
|        | 509    | 7M       | 0.644 1657 87 0.459 1159 167 1.40 | 0.389 943 242 1.66 | 0.382 727 319 1.69 | 0.363 645 377 1.78 | 0.395 521 431 1.63 |
|        | 509    | 8M       | 0.659 1521 88 0.472 1108 170 1.40 | 0.396 943 244 1.66 | 0.384 727 319 1.72 | 0.363 640 383 1.79 | 0.388 511 447 1.69 |
|        | 509    | 9M       | 0.675 1469 89 0.402 1072 172 1.64 | 0.411 973 248 1.64 | 0.393 795 521 1.72 | 0.374 615 366 1.80 | 0.392 501 452 1.72 |
|        | 509    | 10M      | 0.666 1437 90 0.405 1061 172 1.41 | 0.420 946 250 1.63 | 0.404 788 524 1.70 | 0.379 600 391 1.81 | 0.399 489 456 1.72 |
|        | 509    | 100M     | 0.674 1305 92 0.522 982 175 1.43 | 0.445 956 253 1.68 | 0.430 835 529 1.74 | 0.416 648 403 1.80 | 0.435 452 459 1.72 |
|        | 509    | 101M     | 0.674 1305 92 0.522 982 175 1.43 | 0.445 956 253 1.68 | 0.430 835 529 1.74 | 0.416 648 403 1.80 | 0.435 452 459 1.72 |
|        | 509    | 102M     | 0.674 1305 92 0.522 982 175 1.43 | 0.445 956 253 1.68 | 0.430 835 529 1.74 | 0.416 648 403 1.80 | 0.435 452 459 1.72 |

**Table 1:** Benchmarks for directly-programmed NetDescriptions

In general, as long as the heap is small in comparison with the space requirements of the current run, the run-time system spends a much higher part of its time performing garbage collection — this manifests itself in low "productivity" entries in the tables below in the rows with small fixed heap sizes and with "dft.". (The amount of space that is allocated on the heap by any given task varies only minimally with different heap and parallelism settings.) Not limiting the heap size (with "-Msize") on longer-running tasks may lead the run-time system to use a heap that is larger than the available physical memory, leading to drastic performance loss dues to swapping of memory pages to peripheral storage. For tasks that actually do use large heap space, not fixing the start heap size (with "-H size") on longer-running tasks may lead the run-time system to use a heap that is larger than the available physical memory, leading to drastic performance loss. For tasks that actually do use large heap space, not fixing the start heap size (with "-H size") on longer-running tasks may lead the run-time system to use a heap that is larger than the available physical memory, leading to drastic performance loss dues to swapping of memory pages to peripheral storage.
A Simple Parallel Implementation of Interaction Nets in Haskell

The GHC run-time system also provides finer control over the initial heap size, and over the size of the increments; we did not experiment with these here.

Over its whole run-time, \texttt{ackND 3 6} allocates 880MB on the heap, and \texttt{ackND 3 7} allocates 3.5GB. If such small tasks are given large heaps, this leads to significant slow-down. As can be seen for \texttt{ackND 3 8}, which allocates 14GB, giving larger processes a generous fixed heap produces a performance that is closer to the optimum than using the default settings.

On an 8-core 16-hyperthread 2.4GHz Xeon 8870, each of the examples we tried so far has a maximum number of cores beyond which adding cores slows down reduction, see Table 2. This is an example of the effect of diminishing gains of adding processors to a parallel workload that does not split into a sufficient number of sufficiently large independent pieces: The overhead of synchronisation in such a context makes it unfeasible to profit from the computing power of added cores beyond a task-dependent threshold.

Table 2 contains timings for running our \texttt{RunInets} interpreter on a collection of \texttt{Inets} programs mostly derived from programs in [HJ12] by replacing the main \texttt{nets} with larger examples. The last two columns contain timings for running the compiled programs using the \texttt{Inets} compiler of [HJ12], and the quotient of our \texttt{-.N1} time with this run-time.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
expr & N1 & N2 & N\texttt{\texttt{\texttt{\texttt{-}}}N3} & N\texttt{\texttt{\texttt{\texttt{-}}}N4} & N\texttt{\texttt{\texttt{\texttt{-}}}N5} & N\texttt{\texttt{\texttt{\texttt{-}}}N6} & N\texttt{\texttt{\texttt{\texttt{-}}}N7} & N\texttt{\texttt{\texttt{\texttt{-}}}N8} & N\texttt{\texttt{\texttt{\texttt{-}}}N9} & N\texttt{\texttt{\texttt{\texttt{-}}}N10} & N\texttt{\texttt{\texttt{\texttt{-}}}N11} & N\texttt{\texttt{\texttt{\texttt{-}}}N12} & speedup factor over \texttt{-N1} \\
\hline
fib 28 & 63.381 & 40.173 & 22.495 & 19.389 & 16.572 & 17.640 & 16.618 & 17.234 & 1.58 & 2.83 & 3.28 & 3.84 & 3.60 & 3.83 & 3.69 \\
fib 30 & 223.291 & 68.377 & 63.488 & 58.204 & 60.160 & 62.559 & 3.27 & 3.52 & 3.84 & 3.71 & 3.57 \\
ack 3 7 & 5.900 & 4.177 & 3.234 & 3.889 & 3.786 & 4.042 & 4.033 & 4.170 & 1.41 & 1.82 & 1.52 & 1.56 & 1.46 & 1.46 & 1.41 \\
\hline
\end{tabular}
\caption{16-core Benchmarks for directly-programmed \texttt{NetDescriptions}}
\end{table}

of the effect of diminishing gains of adding processors to a parallel workload that does not split into a sufficient number of sufficiently large independent pieces: The overhead of synchronisation in such a context makes it unfeasible to profit from the computing power of added cores beyond a task-dependent threshold.

Table 3 contains timings for running our \texttt{RunInets} interpreter on a collection of \texttt{Inets} programs mostly derived from programs in [HJ12] by replacing the main \texttt{nets} with larger examples. The last two columns contain timings for running the compiled programs using the \texttt{Inets} compiler of [HJ12], and the quotient of our \texttt{-.N1} time with this run-time.

Ackerman.inet from [HJ12] uses a (totalised) predecessor function; Ack.inet is a direct translation of the rules in \texttt{ackND}. The counts reported by the \texttt{Inets} implementation indicate that Ackerman.inet requires almost exactly 1.5 times the number of rule applications of Ack.inet; \texttt{Inets}-compiled executables and our \texttt{RunInets} take roughly 1.6 times the time.

fib.inet is a direct translation of our \texttt{fibND} implementation into \texttt{Inets}, and works, like both Ackerman functions, on unary natural numbers constructed from \texttt{S} and \texttt{Z}. We found that \texttt{fib.inet} performs roughly 20% more allocation than \texttt{fibND}, which will be due to the overhead of transforming an Expression-based \texttt{NetDescription} into Value-based for each rule application (even though there are no expressions to evaluate in this example that does not use attributes). However, it appears that the difference in run times is, as for \texttt{Ack.inet} versus \texttt{ackND}, much less — this should be due to the fact that the overhead is not slowed down by concurrency synchronisation.

fibonacci.inet from [HJ12] carries arguments and results in node attributes, and uses implementation-provided addition of integer attributes instead of recursing over predecessors like \texttt{fibND}. It therefore has significantly less work to do than \texttt{fibND}.

sort.inet from \texttt{Inets} is an implementation of bubble sort on lists; it uses an int-valued agent attribute to carry the list elements, so element comparisons are performed as part of choosing the RHS of conditional rules. The counter results of the \texttt{Inets} runs show that this performs exactly \((n/2 + 1) \cdot (n + 1)\) interactions for a randomly generated start list with even length \(n\). This pattern fits some of the \texttt{RunInets} times in Table 3 exactly, while other \texttt{RunInets} times appear to exhibit a worse asymptotic behaviour; I suggest that this is due to the fact that I used the same heap sizes for different sort argument sizes instead of trying to identify respective optimal heap sizes.

On the whole, on a single core, \texttt{RunInets} typically takes about 10 to 20 times the time of the \texttt{Inets}-compiled executables, which is to be expected for an interpreted implementation.
## Table 3: Benchmarks for Inets programs

Just adding cores to a Runlnets run without any heap settings (see the “df’t.” rows) appears to produce relatively nice speeds for fine-grained parallelism, but one has to be aware that the single-
core execution in that case typically was spending a far larger portion of its time in garbage collection
than the multi-core versions. (This applies also for “relatively small” fixed heaps.)

It appears to be more honest to consider the speed-ups compared to single-core executions with a
“good” fixed heap setting; the fastest runs on our six-core machine with our parallel interpreter all use
five or six cores, and tend to take only about five to six times as long as the compiled Inets runs on a
single core.

(For reasons I have not investigated, the Inets-compiled executables crashed for the larger fib.inet runs after
producing partial output; on a modified version (fibNat.inet) that converts results from unary representation to int
attributes, all Inets runs crashed. For sort.inet, the Inets version was originally changed only by adding longer
argument lists to the start net; beyond 500 elements, this lead to stack overflow errors in the javacc-generated
parser. Changing the start net definition to a sequence of equations each adding a smaller chunk to the list allowed
us to make some progress, but beyond 1000 elements, a different stack overflow occurred.)

6 Conclusion

Interaction nets as an “inherently parallel” execution model promise large speed-ups via parallelisation,
but accessible platforms for experimentation are still missing.

Using Concurrent Haskell to implement interaction nets understood as an execution mechanism, we
achieved a simple and easily understandable implementation, the entire core of which could be presented
in just a bit more than three pages of literate code. By having added support for the Inets file format,
we enable experimentation with interaction net definitions in the shape used by most of the current
interaction net literature — with the restriction that a consistent polarity assignment must be possible
(which is also one of the conditions of Lafont [Laf90] for deadlock safety).

Keeping in mind that, in our straight-forward ultrafine-grained implementation, the concurrent inter-
action net rules reduce a heavily shared structure, and given that we made no effort to enable coarse-grain
parallelism, the speed-ups achieved on the usual microbenchmarks are actually surprisingly good, and
we expect even better behaviour on rules with larger right-hand sides that give rise to more sparsely
connected nets.

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