Functions Compute, Relations Co-ordinate

Manuel M. T. Chakravarty

Technische Universität Berlin / GMD FIRST

1. Declarative parallel programming (GOFFIN)
2. Semantic framework (logic and operational semantics)
3. Multi-threaded execution model (to hide latencies)

DECLARATIVE PARALLEL PROGRAMMING

abstraction $\Rightarrow$ portability

clean semantics $\Rightarrow$
- automatic parallelization (exploits freedom in the evaluation order)
- optimizing transformations (alleviate inefficiencies due to abstraction)

automatic parallelization

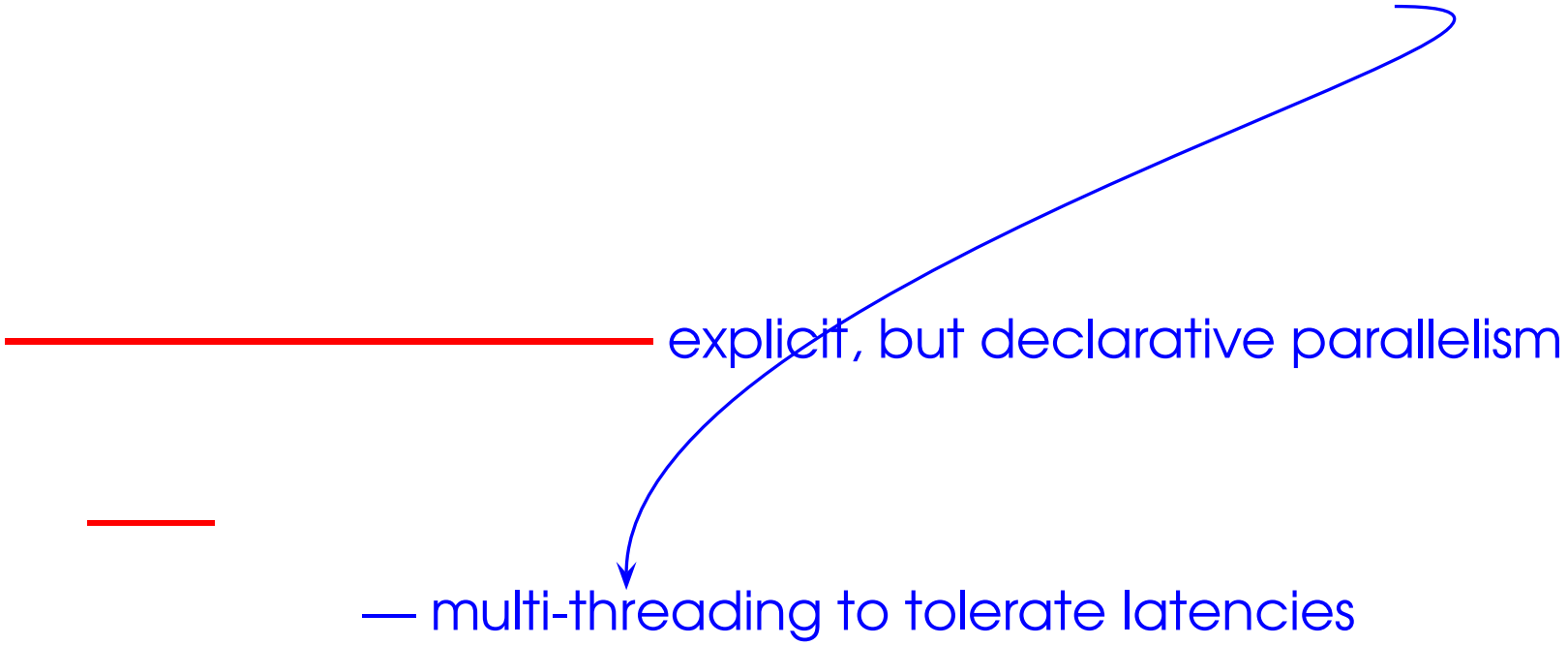
$\Downarrow$

poor performance

$\Uparrow$

irregular access to data structures

(across PE boundaries)


explicit, but declarative parallelism
— multi-threading to tolerate latencies

What is declarative parallelism?

declarative – abstract semantics corresponds to mathematical logic

parallelism – operational semantics defines parallel behaviour

computation	step-at-a-time activities	functional specification
co-ordination	creates & composes activities and organises communication	relational description
	(Carriero & Gelernter 1992)	(Chakravarty, Köhler, Guo & Lock 1995)

Goffin (Chakravarty, Köhler, Guo & Lock 1997):

- ➜ computational sublanguage: Haskell
- ➜ co-ordinating sublanguage:
  - a new type statically identifies co-ordinative agents
  - parallel & sequential composition, synchronization & communication, committed-choice indeterminism

Properties of the language:

- ➜ type system preserves the semantics of Haskell
- ➜ supports the definition of higher-order co-ordination forms (skeletons)

Contributions of the reported work:

- ➜ abstract and operational semantics for GOFFIN-like languages
- ➜ implementation technology for GOFFIN-like languages

$$
\begin{array}{lll}
dc & :: & (\alpha \to Bool) \\
 & \to & (\alpha \to \beta) \\
 & \to & (\alpha \to (\alpha, \alpha)) \\
 & \to & (\beta \to \beta \to \beta) \\
 & \to & (\alpha \to \beta \to O)
\end{array}
$$

$$
\begin{array}{lll}
dc\ \ istriv\ solve\ split\ merge\ p\ s & & \\
\quad \mid istriv\ p & \Rightarrow & \{s \leftarrow solve\ p\} \\
\quad \mid otherwise & \Rightarrow & \{p1\,, p2\,, s1\,, s2 \\
 & & \quad \textbf{in} \\
 & & \qquad (p1\,, p2) \leftarrow split\ p\,, \\
 & & \qquad rdc\ p1\ s1\,, \\
 & & \qquad rdc\ p2\ s2\,, \\
 & & \qquad s \leftarrow merge\ s1\ s2\} \\
 & & \quad \textbf{where} \\
 & & \qquad rdc = dc\ istriv\ solve\ split\ merge
\end{array}
$$

$$
\begin{array}{lcl}
msort & :: & Ord\ \alpha \Rightarrow [\alpha] \rightarrow [\alpha] \rightarrow O \\
msort & = & dc\ ((<= 1)\ .\ length)\ id\ msplit\ mmerge
\end{array}
$$

$$
\begin{array}{lcl}
msplit & :: & [\alpha] \rightarrow ([\alpha], [\alpha]) \\
msplit\ l & = & splitAt\ (length\ l\ `div`\ 2)\ l
\end{array}
$$

$$
\begin{array}{lcl}
mmerge & :: & Ord\ \alpha \Rightarrow [\alpha] \rightarrow [\alpha] \rightarrow [\alpha] \\
mmerge\ []\ \ \ \ ys & = & ys \\
mmerge\ xs\ \ \ \ [] & = & xs \\
mmerge\ (x : xs)\ (y : ys)\ \ |\ x < y & = & x : mmerge\ xs\ (y : ys) \\
\qquad\qquad\qquad\qquad\ \ |\ otherwise & = & y : mmerge\ (x : xs)\ ys
\end{array}
$$

$$
\begin{array}{lcl}
msort & :: & Ord\ a \Rightarrow [\alpha] \rightarrow [\alpha] \rightarrow O \\
msort & = & dc\ ((<= threshold)\ .\ length)\ seqsort\ msplit\ mmerge
\end{array}
$$

SEMANTIC FRAMEWORK

$\mathcal{D}$—a kernel language for GOFFIN

typed lambda calculus with some syntactic sugar

$\lambda v.E$	abstraction	$E_1\ E_2$	application
$a\ \overline{E}$	constructor term	case E of $\overline{X}$	case selection
let $\overline{B}$ in E	local binding	$E{\downarrow}$	dereferencing

co-ordinating agents of type o

0	failure	1	success
$A_1 \parallel A_2$	parallel comp.	$A_1 \Rightarrow A_2$	sequential comp.
$\nu x.E$	unbound var.	$E_1 \doteq E_2$	eq. constraint

$\overline{v}_1 : \overline{G}_1 \rightarrow E_1 \,[]\, \cdots \,[]\, \overline{v}_n : \overline{G}_n \rightarrow E_n$ choice expression

Examples: $\nu x, y.(x \doteq f\ a) \parallel (y \doteq g\ b) \parallel p\ x\ y$ and $\lambda p_1, p_2.(p_1 \parallel p_2)$

Classical logic cannot properly model

➜ committed-choice indeterminism

$$G_1 \to E_1 \,[\!]\, G_2 \to E_2 \qquad \text{where } G_1 \text{ and } G_2 \text{ overlap}$$

➜ rewriting (no concept of consumption)

An alternative: Girard's *linear logic*

➜ weakening and contraction not as structural rules

➜ additive & multiplicative version of the connectives

➜ explicit control over resources (modalities)

Abstract semantics for $\mathcal{D}$ on the basis of linear logic:

➜ each $\mathcal{D}$ expression E corresponds to a formula $\mathcal{E}[\![E]\!]$

➜ the value of E is v iff $\mathbf{D} \vdash \forall r.\mathcal{E}[\![E]\!]\, r \multimap (r\, v \parr \cdots)$
(⊸ denotes linear implementation)

Derivation of an operational semantics by an operational interpretation of linear logic proofs:

"reduction as deduction" (Guo 1994)

① Linear implication induces a transition relation $\rightrightarrows$:

$$E_1 \rightrightarrows E_2 \quad \text{iff} \quad \mathbf{D} \vdash \forall r.\mathcal{E}[\![E_1]\!]\, r \multimap \mathcal{E}[\![E_2]\!]\, r \quad (\text{for all } E_1, E_2 \in \mathcal{D})$$

② Derive transition *rules* from the transition relation $\rightrightarrows$

③ Define the parallel operational semantics by the transition rules

➜ soundness theorem & completeness conjectured

A Multi-threaded Execution Model

Spineless Tagless G-machine: compiled graph-reduction (Peyton Jones 1992)

- ➜ distributed heap implies frequent remote access: latency

$$(a + b) * (c + d) \rightsquigarrow \langle \text{other task} \rangle$$

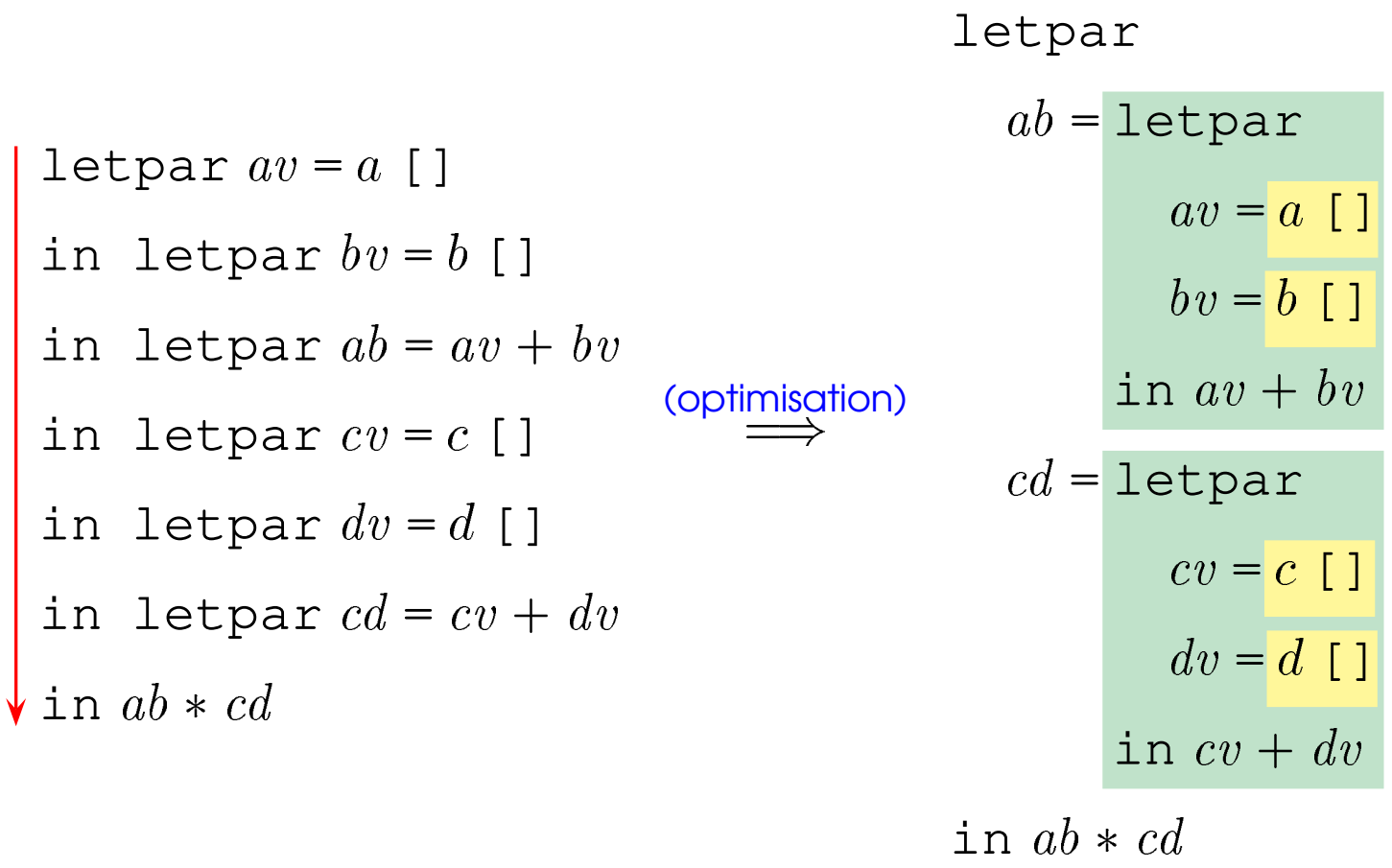
- ➜ task switches are expensive (cache, registers, . . .)

Multi-threading exploits freedom in the evaluation order

- ➜ observe: $c + d$ and $a + b$ share context
- ➜ hide latency by evaluating nearby expressions
- ➜ an abstract notion of threads:

$$\texttt{letpar}\ \underbrace{v_1 = e_1}_{\text{thread \#1}}, \ldots, \underbrace{v_n = e_n}_{\text{thread \#}n}\ \texttt{in}\ e$$

Thread partitioning as source-to-source transformation:



Extension of the Spineless Tagless G-machine:

- ➜ co-ordinating agents
- ➜ multi-threading based on the new `letpar` construct
- ➜ formalized in Haskell (executable specification)

Prototypical implementation of the new abstract machine:

- ➜ emulator
- ➜ determines the *depth* and *work* complexity

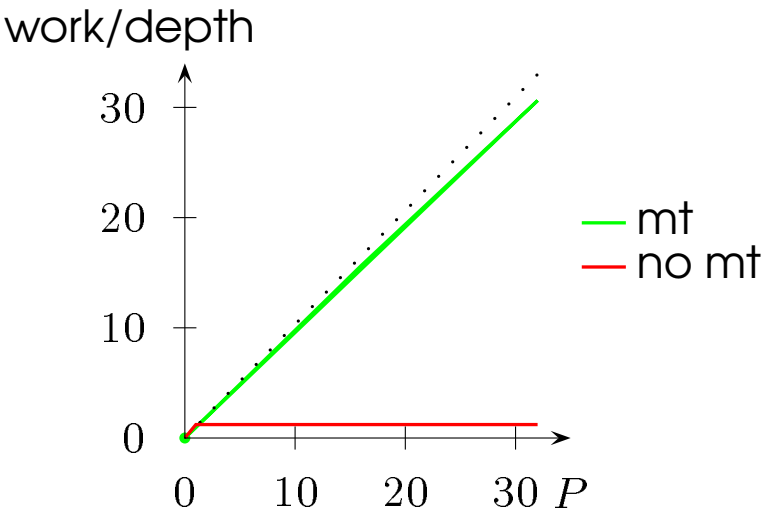
depth	–	critical path
work	–	sequential complexity
work/depth	–	average parallelism

An example ($farm$ is a parallel variant of map):

$$
\begin{aligned}
&farm && :: (\alpha \to \beta) \to [\alpha] \to [\beta] \to O \\
&farm\ f\ []\ r && = \{r \leftarrow []\} \\
&farm\ f\ (x : xs)\ r && = \{ys\ \mathbf{in}\ r \leftarrow (f\ x) : ys, farm\ f\ xs\ ys\}
\end{aligned}
$$

$$
\begin{aligned}
&sum && :: [Int] \to Int \\
&sum\ [] && = 0 \\
&sum\ (x : xs) && = x + sum\ xs
\end{aligned}
$$

$$\{result, l'\ \mathbf{in}\ farm\ f\ l\ l', result \leftarrow sum\ l'\}$$



SUMMARY

$\mathcal{D}$ as a kernel language for GOFFIN:

- ➜ abstract semantics by an encoding into linear logic
- ➜ derivation of a parallel operational semantics
- ➜ soundness & completeness

Extension of the Spineless Tagless G-machine:

- ➜ multi-threading by an abstract notion of threads
- ➜ first experimental results support the expected behaviour

Future work:

- ➜ algebraic semantics
- ➜ alternative logics
- ➜ completion of a compiler
- ➜ extension towards distributed computing