COMP3161/9164
Concepts of Programming Languages

# Haskell Concurrency and STM

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# Shared Data

Consider the **Readers and Writers** problem:

**Problem**

We have a large shared data structure, that can't be updated in one atomic step. Writers are updating it, and readers try to retrieve a coherent copy of it.

We want:

- *Atomicity*: partial updates are not observable.
- *Consistency*: any reader that starts after a finished update will see that update.
- Minimal *waiting*.

# A Crappy Solution

Treat both reads and updates as critical sections — use any old critical section solution (locks, etc.) to sequentialise all reads and writes.

## Observation

Updates are *atomic* and reads are *consistent*—but reads can't happen concurrently, which leads to unnecessary *contention*.

# A Better Solution

A more elaborate locking mechanism (*condition variables*) could be used to to allow multiple concurrent readers. Writers still require exclusive access.

## Observation

This reduces contention. We can't let updates execute concurrently with reads; otherwise, partial updates would be observable.

# Reading and Writing

**Complication**

Suppose we don't want readers to wait (much) while an update is performed. Instead, we'll give them an *older version* of the data.

**Trick**: A writer creates *their own local copy* of the data, and then updates just the *pointer* to the data.

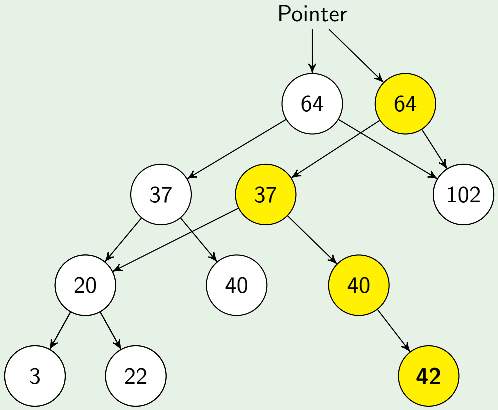
**Atomicity** The only shared write is now just to one pointer.

**Consistency** Reads that start before the pointer update get the older version, but reads that start after get the latest.

# Persistent Data Structures

Copying is $\mathcal{O}(n)$ in the worst case, but we can do better for many tree-like structures.

## Example (Binary Search Tree)



# Purely Functional Data Structures

Persistent data structures that use of copying (rather than mutation) are called *purely functional* data structures. Operations on them can be expressed as mathematical functions that, given an input structure, return a *new* output structure:

$$
\begin{array}{lcl}
\mathit{insert}\ v\ \mathrm{Leaf} & = & \mathrm{Branch}\ v\ \mathrm{Leaf}\ \mathrm{Leaf} \\
\mathit{insert}\ v\ (\mathrm{Branch}\ x\ l\ r) & = & \textsf{if}\ v \leq x\ \textsf{then} \\
 & & \quad \mathrm{Branch}\ x\ (\mathit{insert}\ v\ l)\ r \\
 & & \textsf{else} \\
 & & \quad \mathrm{Branch}\ x\ l\ (\mathit{insert}\ v\ r)
\end{array}
$$

# Computing with Functions

We model processes in Haskell using the $\mathrm{IO}$ type. We'll treat $\mathrm{IO}$ as an abstract type for now, and give it a formal semantics later if we have time:

$\mathrm{IO}\ \tau\ =$ A (possibly effectful) process that, when executed, produces a result of type $\tau$

Note the semantics of *evaluation* and *execution* are different things.

# Building up IO

Recall monads:

$$
\begin{aligned}
&\mathit{return} :: \forall a.\ a \to \mathrm{IO}\ a \\
&(\gg\!=) :: \forall a\ b.\ \mathrm{IO}\ a \to (a \to \mathrm{IO}\ b) \to \mathrm{IO}\ b \\
&\mathit{getChar} :: \mathrm{IO}\ \mathrm{Char} \\
&\mathit{putChar} :: \mathrm{Char} \to \mathrm{IO}\ ()
\end{aligned}
$$

**Example (Echo)**

$$
\begin{aligned}
&\mathit{echo} :: \mathrm{IO}\ () \\
&\mathit{echo} = \mathit{getChar} \gg\!= (\lambda x.\ \mathit{putChar}\ x \gg\!= \lambda y.\ \mathit{echo})
\end{aligned}
$$

Or, with **do** notation:

$$
\begin{aligned}
&\mathit{echo} :: \mathrm{IO}\ () \\
&\mathit{echo} = \mathsf{do}\ \ x \leftarrow \mathit{getChar} \\
&\qquad\qquad\quad\ \ \mathit{putChar}\ x \\
&\qquad\qquad\quad\ \ \mathit{echo}
\end{aligned}
$$

# Adding Concurrency

We can have multiple threads easily enough:

$$\textit{forkIO} :: \mathrm{IO}\ () \ \rightarrow \mathrm{IO}\ ()$$

**Example (Dueling Printers)**

$$\begin{array}{l} \text{let } \textit{loop}\ c = \textbf{do}\ \textit{putChar}\ c; \textit{loop}\ c \\ \text{in } \textbf{do}\ \textit{forkIO}\ (\textit{loop}\ \text{`a'}); \textit{loop}\ \text{`z'} \end{array}$$

But what sort of *synchronisation primitives* are available?

# MVars

The MVar is the simplest synchronisation primitive in Haskell. It can be thought of as a shared box which holds at most one value.

Processes must take the value out of a full box to read it, and must put a value into an empty box to update it.

**MVar Functions**

| | |
|---|---|
| $\mathit{newMVar} :: \forall a.\ a \rightarrow \mathrm{IO}\ (\mathrm{MVar}\ a)$ | Create a new MVar |
| $\mathit{takeMVar} :: \forall a.\ \mathrm{MVar}\ a \rightarrow \mathrm{IO}\ a$ | Read/remove the value |
| $\mathit{putMVar} :: \forall a.\ \mathrm{MVar}\ a \rightarrow a \rightarrow \mathrm{IO}\ ()$ | Update/insert a value |

Taking from an empty MVar or putting into a full one results in blocking.
An MVar can be thought of as channel containing at most one value.

# Readers and Writers

We can treat MVars as shared variables with some definitions:

$$
\begin{array}{l}
\mathit{writeMVar}\ m\ v = \mathbf{do}\ \mathit{takeMVar}\ m; \mathit{putMVar}\ m\ v \\
\mathit{readMVar}\ m = \mathbf{do}\ v \leftarrow \mathit{takeMVar}\ m; \mathit{putMVar}\ m\ v; \mathit{return}\ v
\end{array}
$$

$$
\begin{array}{l}
\mathit{problem} :: \mathit{DB} \rightarrow \mathrm{IO}\ () \\
\mathit{problem}\ \mathit{initial} = \mathbf{do} \\
\quad \mathit{db} \leftarrow \mathit{newMVar}\ \mathit{initial} \\
\quad \mathit{wl} \leftarrow \mathit{newMVar}\ () \\
\quad \mathbf{let}\ \mathit{reader} = \mathit{readMVar}\ \mathit{db} \gg\!= \cdots \\
\quad \mathbf{let}\ \mathit{writer} = \mathbf{do} \\
\quad\quad \mathit{takeMVar}\ \mathit{wl} \\
\quad\quad d \leftarrow \mathit{readMVar}\ \mathit{db} \\
\quad\quad \mathbf{let}\ d' = \mathit{update}\ d \\
\quad\quad \mathit{evaluate}\ d' \\
\quad\quad \mathit{writeMVar}\ \mathit{db}\ d' \\
\quad\quad \mathit{putMVar}\ \mathit{wl}\ ()
\end{array}
$$

# Fairness

Each MVar has an attached FIFO queue, so GHC Haskell can ensure the following fairness property:

> *No thread can be blocked indefinitely on an MVar unless another thread holds that MVar indefinitely.*

# The Problem with Locks

## Problem

Write a procedure to transfer money from one bank account to another. To keep things simple, both accounts are held in memory: no interaction with databases is required. The procedure must operate correctly in a concurrent program, in which many threads may call transfer simultaneously. No thread should be able to observe a state in which the money has left one account, but not arrived in the other (or vice versa).

# The Problem with Locks

Assume some infrastructure for accounts:

$$\textbf{type}\ \mathrm{Balance} = \mathrm{Int}$$
$$\textbf{type}\ \mathrm{Account} = \mathrm{MVar}\ \mathrm{Balance}$$

$$\mathit{withdraw} :: \mathrm{Account} \rightarrow \mathrm{Int} \rightarrow \mathrm{IO}\ ()$$
$$\mathit{withdraw}\ a\ m = \mathit{takeMVar}\ a \gg\!= (\mathit{putMVar}\ a\ \circ \mathit{subtract}\ m)$$

$$\mathit{deposit} :: \mathrm{Account} \rightarrow \mathrm{Int} \rightarrow \mathrm{IO}\ ()$$
$$\mathit{deposit}\ a\ m = \mathit{withdraw}\ a\ (-m)$$

# Attempt #1

$$\mathit{transfer}\ f\ t\ m = \textbf{do}\ \mathit{withdraw}\ f\ m; \mathit{deposit}\ t\ m$$

**Problem**

The intermediate states where a transaction has only been partially completed are externally observable.

In a bank, we might want the invariant that at all points during the transfer, the total amount of money in the system remains constant. We should have no money go missing.

# Attempt #2

$$
\begin{aligned}
&\mathit{transfer}\ f\ t\ m = \mathbf{do} \\
&\quad \mathit{fb} \leftarrow \mathit{takeMVar}\ f \\
&\quad \mathit{tb} \leftarrow \mathit{takeMVar}\ t \\
&\quad \mathit{putMVar}\ t\ (\mathit{tb} + m) \\
&\quad \mathit{putMVar}\ f\ (\mathit{fb} - m)
\end{aligned}
$$

## Problem

We can have *deadlock* here, when two people transfer to each other simultaneously and both transfers proceed in lock-step.

Also, we can't just compose our existing *withdrawal* and *deposit* operations. That's sad.

# Solution

We should enforce a *global* ordering of locks.

$$\textbf{type}\ \text{Account} = (\text{MVar Balance}, \text{AccountNo})$$

$$
\begin{array}{l}
\mathit{transfer}\ (f, \mathit{fa})\ (t, \mathit{ta})\ m = \textbf{do} \\
\quad (\mathit{fb}, \mathit{tb}) \leftarrow \textbf{if}\ \mathit{fa} \leq \mathit{ta} \\
\qquad \textbf{then do} \\
\qquad\quad \mathit{fb} \leftarrow \mathit{takeMVar}\ f \\
\qquad\quad \mathit{tb} \leftarrow \mathit{takeMVar}\ t \\
\qquad\quad \mathit{pure}\ (\mathit{fb}, \mathit{tb}) \\
\qquad \textbf{else do} \\
\qquad\quad \mathit{tb} \leftarrow \mathit{takeMVar}\ t \\
\qquad\quad \mathit{fb} \leftarrow \mathit{takeMVar}\ f \\
\qquad\quad \mathit{pure}\ (\mathit{fb}, \mathit{tb}) \\
\quad \mathit{putMVar}\ t\ (\mathit{tb} + m) \\
\quad \mathit{putMVar}\ f\ (\mathit{fb} - m)
\end{array}
$$

# It Gets Complicated

**Problem**

Now suppose that some accounts can be configured with a "backup" account, that is used if insufficient funds are available in the default account.

Should you take the lock for the backup account?

**To make life even harder**: What if we want to *block* if insufficient funds are available?

# Conclusion

*Lock-based methods* have their place, but from a software engineering perspective they're a nightmare.

- Remember not to take too many locks.
- Remember not to take too few locks.
- Remember what locks correspond to each piece of shared data.
- Remember not to take the locks in the wrong order.
- Remember to deal with locks when an error occurs.
- Remember to signal condition variables and release locks at the right time.

Most importantly, *modular programming* becomes impossible.

# The Solution

Represent an account as a simple shared variable containing the balance.

$$
\begin{array}{l}
\mathit{transfer}\ f\ t\ m = \mathit{atomically}\ \$\ \mathrm{do} \\
\qquad \mathit{withdraw}\ f\ m \\
\qquad \mathit{deposit}\ t\ m
\end{array}
$$

Where *atomically* $P$ guarantees:

**Atomicity** The effects of the action $P$ become visible all at once.

**Isolation** The effects of action $P$ is not affected by any other threads.

**Problem**

How can we implement *atomically*?

# The Global Lock

We can adopt the solution of certain reptilian programming languages.

## Problem

Atomicity is guaranteed, but what about *isolation*?

Also, performance is predictably garbage.

# Ensuring Isolation

Rather than use regular shared variables, use special *transactional variables*.

$$\begin{array}{lll} \mathit{newTVar} & :: & a \rightarrow \mathrm{STM}\ (\mathrm{TVar}\ a) \\ \mathit{readTVar} & :: & \mathrm{TVar}\ a \rightarrow \mathrm{STM}\ a \\ \mathit{writeTVar} & :: & \mathrm{TVar}\ a \rightarrow a \rightarrow \mathrm{STM}\ () \\ & & \\ \mathit{atomically} & :: & \mathrm{STM}\ a \rightarrow \mathrm{IO}\ a \end{array}$$

The type constructor $\mathrm{STM}$ is also an instance of the *Monad* type class, and thus supports the same basic operations as $\mathrm{IO}$.

$$\begin{array}{lll} \mathit{pure} & :: & a \rightarrow \mathrm{STM}\ (\mathrm{TVar}\ a) \\ (\gg\!=) & :: & \mathrm{STM}\ a \rightarrow (a \rightarrow \mathrm{STM}\ b) \rightarrow \mathrm{STM}\ b \end{array}$$

# Implementing Accounts

```
type Account = TVar Int

withdraw :: Account → Int → STM ()
withdraw a m = do
    balance ← readTVar m
    writeTVar a (balance − m)

deposit a m = withdraw a (−m)
```

**Observe**: *withdraw* (resp. *deposit*) can only be called inside an *atomically* ⇒ We have isolation.

But, we'd still like to run more than one transaction at once — one global lock isn't good enough.

# Optimistic Execution

Each transaction (`atomically` block) is executed *optimistically*. This means they do not need to check that they are allowed to execute the transaction first (unlike, say, locks, which prefer a *pessimistic* model).

## Implementation Strategy

Each transaction has an associated *log*, which contains:

- The values written to any $\mathrm{TVar}$s with *writeTVar*.
- The values read from any $\mathrm{TVar}$s with *readTVar*, consulting earlier log entries first.

First the log is *validated*, and, if validation succeeds, changes are *committed*. Validation and commit are *one atomic step*.

What can we do if validation fails? We re-run the transaction!

# Re-running transactions

$$
\begin{array}{l}
\mathit{atomically}\ \$\ \mathrm{do} \\
\quad x \leftarrow \mathit{readTVar}\ \mathit{xv} \\
\quad y \leftarrow \mathit{readTVar}\ \mathit{yv} \\
\quad \mathrm{if}\ x > y\ \mathrm{then}\ \mathit{detonateTNT}\ \mathrm{else}\ \mathit{pure}\ ()
\end{array}
$$

To avoid harmful side-effects, the transaction must be *repeatable*. We can't change the world until *commit* time.

A real implementation is smart enough not to retry with exactly the same schedule.

# Blocking and *retry*

**Problem**

We want to *block* if insufficient funds are available.

We can use the helpful action $\mathit{retry} :: \mathrm{STM}\ a$.

$$
\begin{array}{l}
\mathit{withdraw}' :: \mathrm{Account} \rightarrow \mathrm{Int} \rightarrow \mathrm{STM}\ () \\
\mathit{withdraw}'\ a\ m = \mathbf{do} \\
\quad \mathit{balance} \leftarrow \mathit{readTVar}\ a \\
\quad \mathbf{if}\ m > 0\ \&\&\ m > \mathit{balance}\ \mathbf{then} \\
\quad\quad \mathit{retry} \\
\quad \mathbf{else} \\
\quad\quad \mathit{writeTVar}\ a\ (\mathit{balance} - m)
\end{array}
$$

# Choice and *orElse*

**Problem**

We want to transfer from a backup account if the first account has insufficient funds, and *block* if neither account has insufficient funds.

We can use the helpful action

$$\mathit{orElse} :: \mathrm{STM}\ a \rightarrow \mathrm{STM}\ a \rightarrow \mathrm{STM}\ a$$

$$\begin{aligned}&\mathit{wdBackup} :: \mathrm{Account} \rightarrow \mathrm{Account} \rightarrow \mathrm{Int} \rightarrow \mathrm{STM}\ ()\\&\mathit{wdBackup}\ a_1\ a_2\ m = \mathit{orElse}\ (\mathit{withdraw}'\ a_1\ m)\ (\mathit{withdraw}'\ a_2\ m)\end{aligned}$$

# Evaluating STM

STM is *modular*. We can compose transactions out of smaller transactions. We can hide concurrency behind library boundaries without worrying about deadlock or global invariants.

Lock-free data structures and transactional memory based solutions work well if contention is low and under those circumstances scale better to higher process numbers than lock-based ones.

Most importantly, the resulting code is often simpler and more robust. **Profit!**

# Progress

*One transaction can force another to abort only when it commits.*

*At any time, at least one currently running transaction can successfully commit.*

Traditional deadlock scenarios are impossible, as is cyclic restarting where two transactions constantly cancel each other.

*Starvation* is possible (when?), however uncommon in practice. So, we technically don't have eventual entry.

# Database Guarantees

**Atomicity** ✓ Each transaction should be 'all or nothing'.

**Consistency** ✓ Each transaction in the future sees the effects of transactions in the past.

**Isolation** ✓ The transaction's effect on the state cannot be affected by other transactions.

**Durability** The transaction's effect on the state survives power outages and crashes.

STM gives you 75% of a database system. The Haskell package *acid-state* builds on STM to give you all four.

# That's it

We have now covered all the content in COMP3161/COMP9164. Thanks for sticking with the course.

- **Syntax Foundations**
  Concrete/Abstract Syntax, Ambiguity, HOAS, Binding, Variables, Substitution, $\lambda$-calculus
- **Semantics Foundations**
  Static Semantics, Dynamic Semantics (Small-Step/Big-Step), Abstract Machines, Environments, Stacks, Safety, Liveness, Type Safety (Progress and Preservation)
- **Features**
  - Algebraic Data Types, Recursive Types
  - Exceptions
  - Polymorphism, Type Inference, Unification
  - Overloading, Subtyping, Abstract Data Types
  - Concurrency, Critical Sections, STM

# MyExperience

Please fill out the survey. It helps tremendously.

`https://myexperience.unsw.edu.au`

# Further Learning

- UNSW courses:
  - `COMP3141` — Software System Design and Implementation
  - `COMP6721` — (In-)formal Methods
  - `COMP3131` — Compilers
  - `COMP4141` — Theory of Computation
  - `COMP3151` — Foundations of Concurrency
  - `COMP4161` — Advanced Topics in Verification
  - `COMP3153` — Algorithmic Verification
- Online Learning
  - Oregon Programming Languages Summer School Lectures (`https://www.cs.uoregon.edu/research/summerschool/archives.html`) Videos are available from here! Also some on YouTube.

# What's next?

The exam is on **Monday, 5th of December 2022** at 9am.

- I have posted a sample exam with revision questions.
- The final exam will run similar to the sample exam.
- It runs for 2 hours and 10 minutes.

# Evaluation Semantics

The semantics of Haskell's evaluation are interesting but not particularly relevant for us. We will assume that it happens quietly without a fuss:

$$\begin{array}{llcl} \beta\textbf{-equivalence} & (\lambda x.\ M[x])\ N & \equiv_\beta & M[N] \\ \alpha\textbf{-equivalence} & \lambda x.\ M[x] & \equiv_\alpha & \lambda y.\ M[y] \\ \eta\textbf{-equivalence} & \lambda x.\ M\ x & \equiv_\eta & M \end{array}$$

Let our ambient congruence relation $\equiv$ be $\equiv_{\alpha\beta\eta}$ enriched with the following extra equations, justified by the *monad laws*:

$$\begin{array}{lcl} \mathit{return}\ N \gg\!= M & \equiv & M\ N \\ (X \gg\!= Y) \gg\!= Z & \equiv & X \gg\!= (\lambda x.\ Y\ x \gg\!= Z) \\ X & \equiv & X \gg\!= \mathit{return} \end{array}$$

# Processes

This means that a Haskell expression of type $\mathrm{IO}\ \tau$ for will boil down to either *return* $x$ where $x$ is a value of type $\tau$; or $a \ggg= M$ where $a$ is some *primitive* $\mathrm{IO}$ *action* (*forkIO* $p$, *readMVar* $v$, etc.) and $M$ is some function producing another $\mathrm{IO}\ \tau$. This is the *head normal form* for $\mathrm{IO}$ expressions.

**Definition**

Define a language of *processes* $P$, which contains all (head-normal) expressions of type $\mathrm{IO}\ ()$.

We want to define the semantics of the *execution* of these processes. Let's use *operational semantics*:

$$(\mapsto) \subseteq P \times P$$

# Semantics for forkIO

To model *forkIO*, we need to model the parallel execution of multiple processes in our process language. We shall add a *parallel composition* operator to the language of processes:

$$\begin{array}{rcl} P, Q & ::= & a \gg= M \\ & \mid & \mathit{return}\ () \\ & \mid & P \parallel Q \\ & \mid & \cdots \end{array}$$

And the following ambient congruence equations:

$$\begin{array}{rcl} P \parallel Q & \equiv & Q \parallel P \\ P \parallel (Q \parallel R) & \equiv & (P \parallel Q) \parallel R \end{array}$$

# Semantics for forkIO

If we have multiple processes active, pick one of them non-deterministically to move:

$$\frac{P \mapsto P'}{P \parallel Q \mapsto P' \parallel Q}$$

The *forkIO* operation introduces a new process:

$$(\mathit{forkIO}\ P \gg\!= M) \quad \mapsto \quad P \parallel (\mathit{return}\ () \gg\!= M)$$

# Semantics for MVars

MVars are modelled as a special type of *process*, identified by a *unique name*. Values of $\mathrm{MVar}$ type merely contain the name of the process, so that *putMVar* and friends know where to look.

$$
\begin{array}{rcl}
P, Q & ::= & a \gg\!= M \\
& \mid & \mathit{return}\ () \\
& \mid & P \parallel Q \\
& \mid & \langle\rangle_n \quad \mid \quad \langle v \rangle_n \\
& \mid & \ldots
\end{array}
$$

$$\langle\rangle_n \parallel (\mathit{putMVar}\ \ n\ \ v \gg\!= M) \;\;\mapsto\;\; \langle v \rangle_n \parallel (\mathit{return}\ () \gg\!= M)$$

$$\langle v \rangle_n \parallel (\mathit{takeMVar}\ \ n \gg\!= M) \;\;\mapsto\;\; \langle\rangle_n \parallel (\mathit{return}\ v \gg\!= M)$$

# Semantics for newMVar

We might think that *newMVar* should have semantics like this:

$$\frac{}{(\mathit{newMVar}\ v \gg\!= M) \ \mapsto\ \langle v \rangle_n \parallel (\mathit{return}\ n \gg\!= M)}(n \text{ fresh})$$

But this approach has a number of problems:

- The name $n$ is now globally-scoped, without an explicit binder to introduce it.
- It doesn't accurately model the *lifetime* of the MVar, which should be garbage-collected once all processes that can access it finish.
- It makes MVars *global* objects, so our semantics aren't very *abstract*. We would like local communication to be local in our model.

# Restriction Operator

We introduce a *restriction operator* $\nu$ to our language of processes:

$$\begin{array}{rcl} P, Q & ::= & a \gg= M \\ & \mid & \mathit{return}\ () \\ & \mid & P \parallel Q \\ & \mid & \langle\rangle_n \quad \mid \quad \langle v \rangle_n \\ & \mid & (\nu\ n)\ P \end{array}$$

Writing $(\nu\ n)\ P$ says that the MVar name $n$ is *only* available in process $P$. Mentioning $n$ outside $P$ is not well-formed. We need the following additional congruence equations:

$$\begin{array}{rcll} (\nu\ n)\ (\nu\ m)\ P & \equiv & (\nu\ m)\ (\nu\ n)\ P & \\ (\nu\ n)(P \parallel Q) & \equiv & P \parallel (\nu\ n)\ Q & (\text{if } n \notin P) \end{array}$$

# Better Semantics for newMVar

The rule for *newMVar* is much the same as before, but now we explicitly restrict the MVar to $M$.

$$\frac{}{(\mathit{newMVar}\ v \ggg= M) \ \mapsto\ (\nu\ n)(\langle v\rangle_n \parallel (\mathit{return}\ n \ggg= M))}(n \text{ fresh})$$

We can always execute under a restriction:

$$\frac{P \mapsto P'}{(\nu\ n)\ P \mapsto (\nu\ n)\ P'}$$

**Question**

What happens when you put an MVar inside another MVar?

# Garbage Collection

If an MVar is no longer used, we just replace it with the do-nothing process:

$$\begin{array}{lcl} (\nu\ n)\ \langle\rangle_n & \mapsto & \mathit{return}\ () \\ (\nu\ n)\ \langle v\rangle_n & \mapsto & \mathit{return}\ () \end{array}$$

Extra processes that have outlived their usefulness disappear:

$$\mathit{return}\ () \parallel P \quad \mapsto \quad P$$

# Process Algebra

Our language $P$ is called a *process algebra*, a common means of describing semantics for concurrent programs.

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