Baltic: Service Combinators for Farming Virtual Machines

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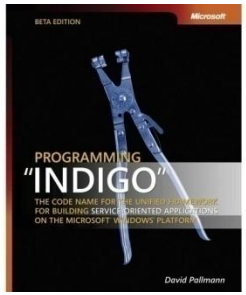
Farms, Roles, Service Orientation

- Abstractly, a **server farm** is a set of servers.
- Each server boots off a **disk image**, eg, the contents of a local hard drive, or an image fetched off the network.
- Each server plays a particular **role**, eg, web server, database.
- We assume the disk images, and hence the behaviour, of each server in a particular role are essentially the same.
- A **service** is a set of **endpoints**, each of which is a communication port implementing a function accessible by RPC
- Server roles are increasingly **service-oriented** in that they are described as **importing** and **exporting** typed endpoints.
- For example, Web Services Description Language (WSDL) is a common format for describing services based on typed SOAP messages.

Three Example Roles

- Our scripting examples concern three web services used as the back end of a web app, the "Adventure Works" website
- The code, from a book on programming .NET 3, is in C#
- Each of the services consists of a single endpoint
- These services have standard WSDL metadata



OrderEntry	Payment	OrderProcessing
• called when a customer completes checkout • OrderW2K3.vhd	• called to authorize payment • PaymentW2K3.vhd	• called to fulfill the order • ProcW2K3.vhd

WSDL Metadata for Services

```
let payment:service =
  {sname = "Payment";
   ops = [{opname = "AuthorizePayment";
           action = "http://tempuri.org/IPayment/AuthorizePayment";
           input = "ProgrammingIndigo.Payment";
           output = "string"}]}
let orderProc:service =
  {sname = "OrderProcessing";
   ops = [{opname = "SubmitOrder";
           action = "http://AdventureWorks/IOrderProcessing/SubmitOrder";
           input = "ProgrammingIndigo.Order";
           output = "unit"}]}
let orderEntry:service =
  {sname = "OrderEntry";
   ops = [{opname = "SubmitOrder";
           action = "http://AdventureWorks/IOrderEntry/SubmitOrder";
           input = "ProgrammingIndigo.Order";
           output = "string"}]}
```

Operating System Virtualization

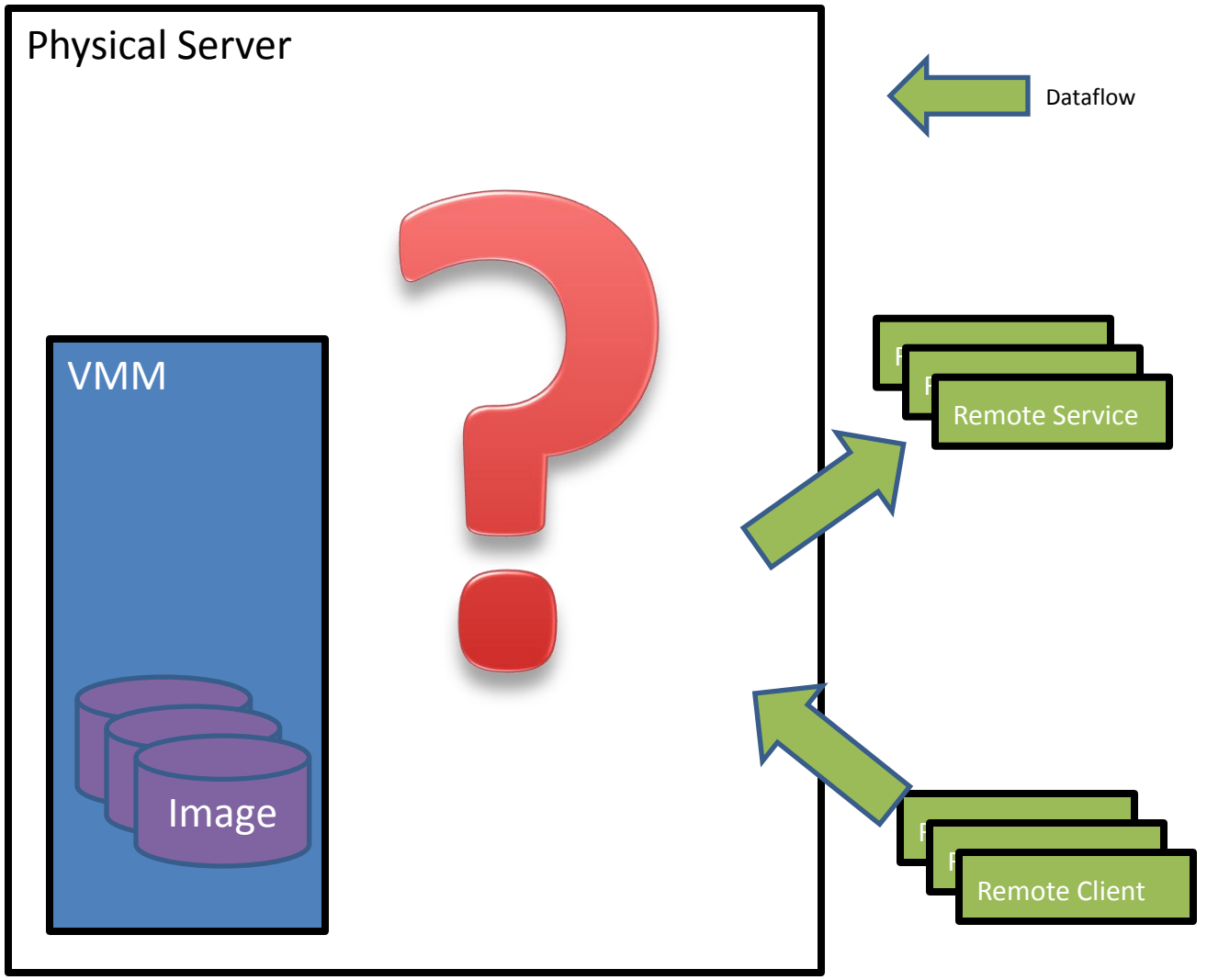
- A **host** OS runs on physical machine and controls its devices, and runs multiple **guest** OSs within VMs
  - Control software known as **virtual machine monitor** (VMM)
  - Guests' disk images held as **virtual hard disk** files on the host
  - VMs attached to **virtual networks**, which may or may not be isolated
- VMM gives guests the illusion of direct access to hardware
  - Not object-oriented runtime with garbage collection, as provided by a language-based VM such as the JVM or CLR
- VMware launch first VMM on commodity x86 hardware in 1999; first server product in 2001
  - Other x86 VMMs include Xen, KVM, and Microsoft Virtual Server
  - OS virtualization on mainframes goes back to VM/370, launched 1972

The Programming Problem

Goal: export services on physical server to remote clients

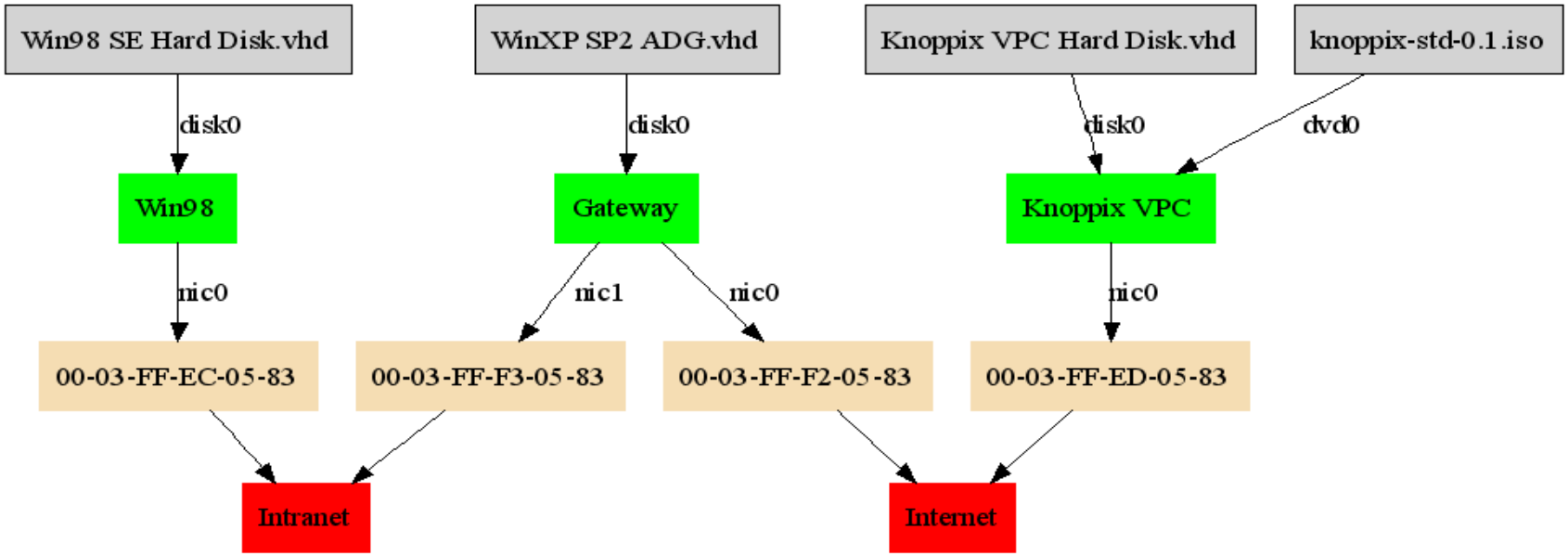
Resources: pre-compiled disk images and remote services

Problem: how to program a VMM to achieve the goal with the resources



Existing APIs: Device Combinators

- Existing APIs for VMMs manipulate a **wiring graph**
  - Each node is a device, eg, disk, machine, network adapter, network, etc
  - Each edge is virtual wiring between devices



Metadata for Disks and I/O

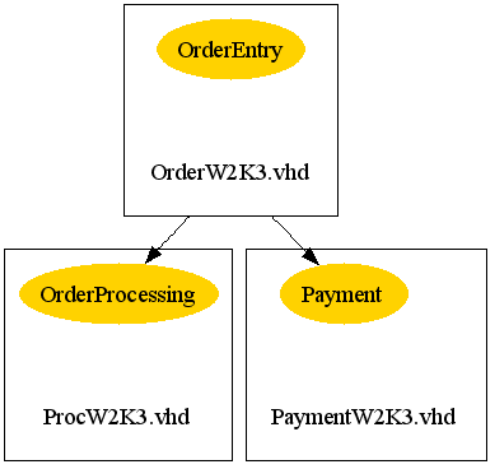
```
let m:metadata =
  [VM {vmname = "OrderEntry"; disk = "OrderW2K3.vhd";
       inputs = [payment; orderProc]; outputs = [("/OrderEntry.svc",orderEntry)]};
  ...
  Import {name="Payment1“; url = http://credit.fr/CA/service.svc ;  service=p ayment};
  ...
  Export {name="OrderEntry“;url = http://localhost:80/OE/service.svc ; service=orderEntry}]
```

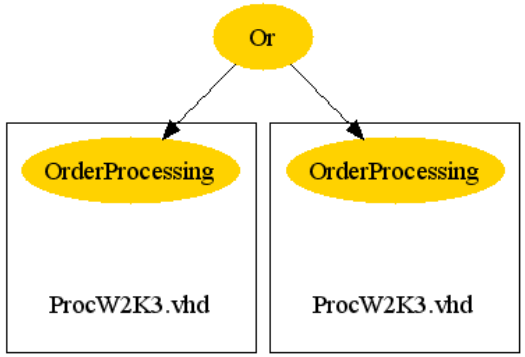
Our Observation: our resources – disks, imports, and exports – can be assigned service-oriented metadata

Our Hypothesis: typed interfaces to our resources, generated from this metadata, are more productive and less error-prone than conventional device-oriented APIs

Baltic API: Service Combinators

- Our API for VMMs manipulates a **call graph**
  - Each node is an endpoint, ie, an RPC implementation, hosted either within a VM or as a separate intermediary
  - Each edge represents a potential RPC
- Each VM is shown as a box
  - the endpoints in the box are its **exported service**
  - the endpoints connected to the box are its **imported service**



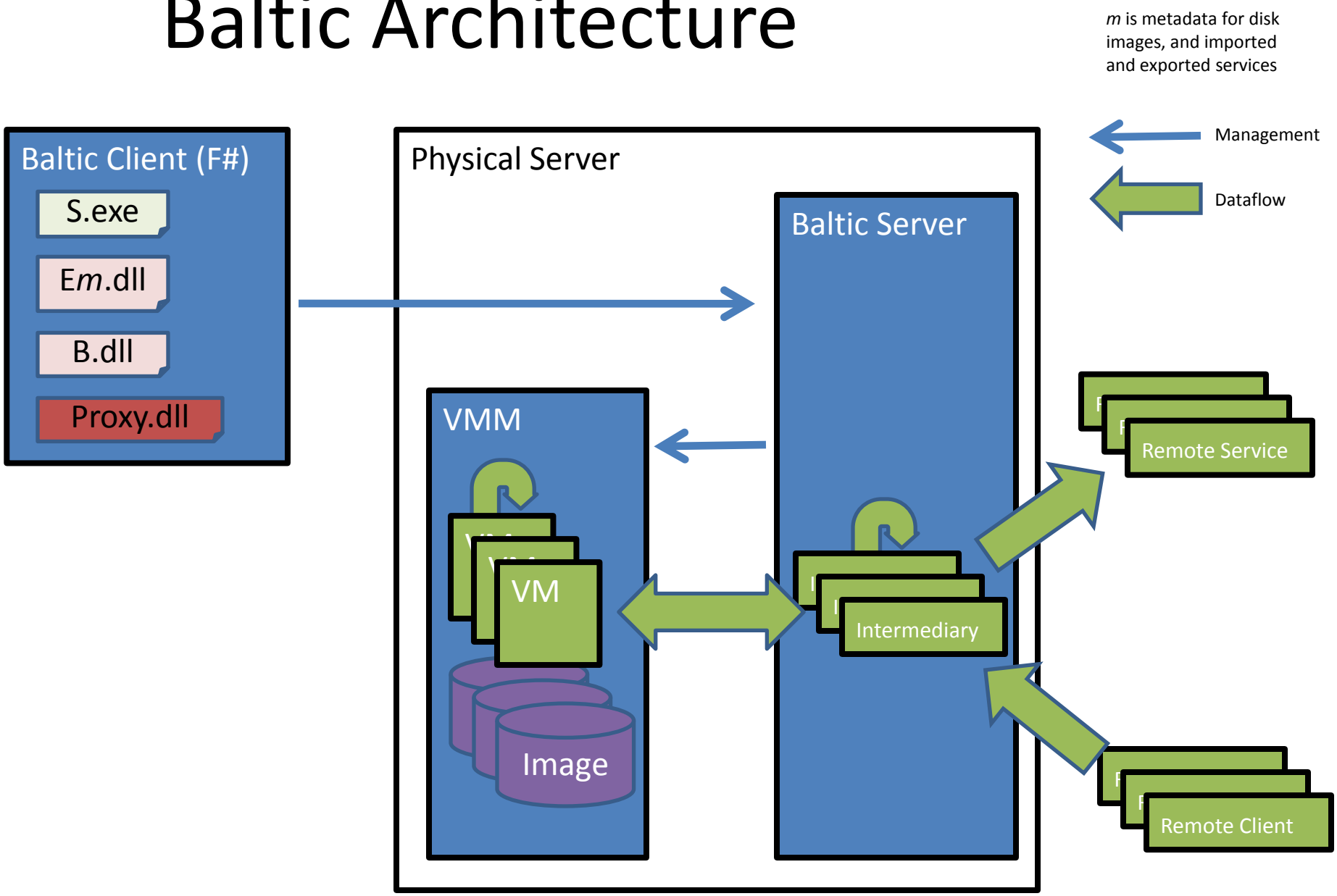


Baltic: Service Combinators

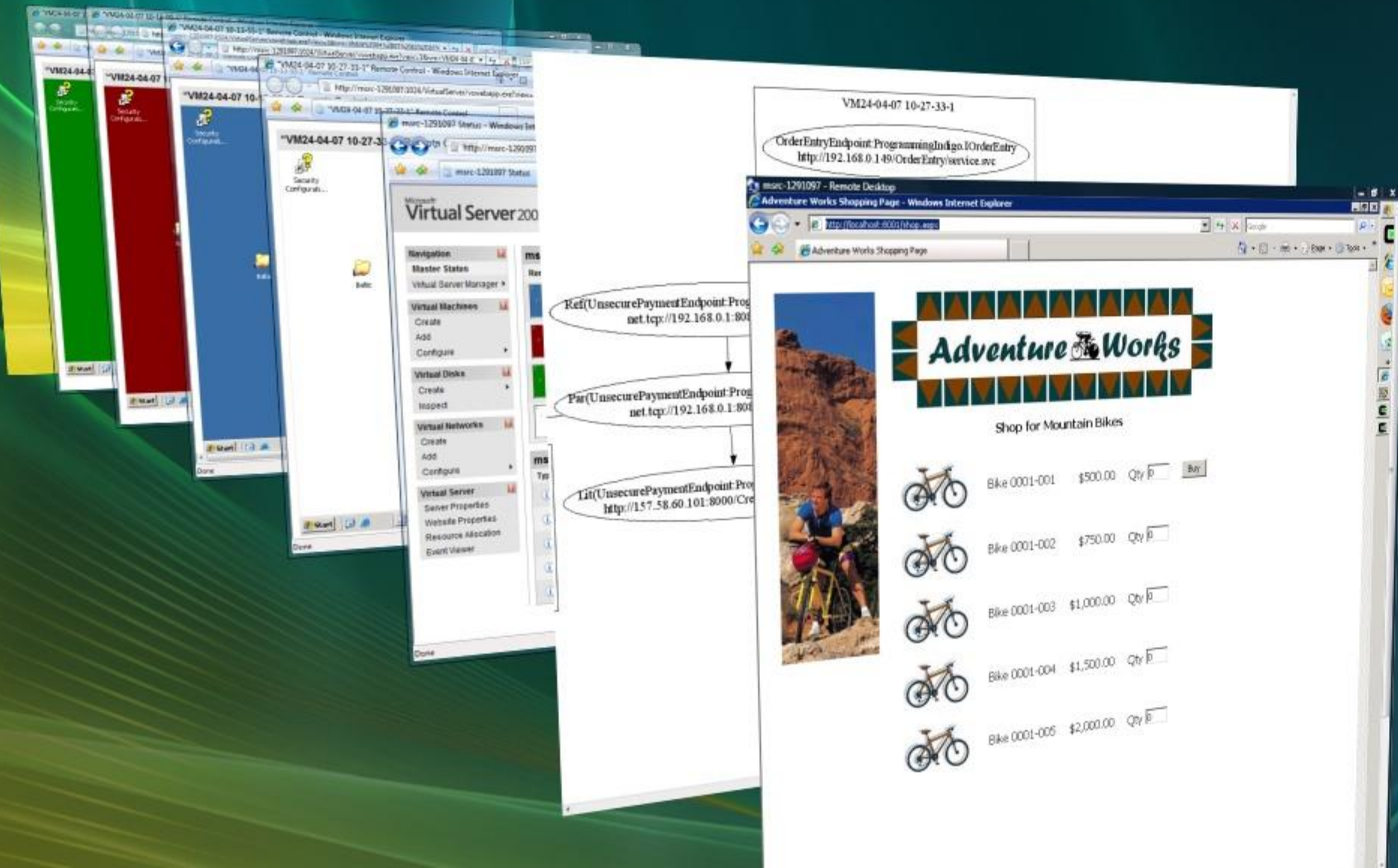
- VMM APIs are an essential piece of the farm management puzzle
- Current **device-oriented APIs** are undoubtedly usable, but:
  - They are low-level – virtual devices and virtual wiring
  - They ignore service-oriented metadata – VMs are simply nodes
  - They are error-prone – no protection from connection errors
- Instead, we propose a higher-level **service-oriented API**
  - Our combinators operate on a call graph – endpoints and potential calls – but are implemented over a device-oriented API
  - We exploit service-oriented metadata (eg WSDL) to generate typed descriptions of server roles and external endpoints – VMs are functions from imported service to exported service
  - A benefit of typing is that various connection errors are detected statically, rather than sometime during execution.

BALTIC ARCHITECTURE, COMBINATOR EXAMPLES

Baltic Architecture



4 VMs, VMM, Baltic, External Client



B.mli

```
type vm
type vm_snapshot
type event = VM_Crash
type ('a,'b) endpoint
type ('a,'b) endpointref
val eOr : ('a,'b) endpoint -> ('a,'b) endpoint -> ('a,'b) endpoint
val ePar : ('a,'b) endpoint -> ('a,'b) endpoint -> ('a,'b) endpoint
val eRef : ('a,'b) endpoint -> ('a,'b) endpoint * ('a,'b) endpointref
val eRefUpdate : ('a,'b) endpointref -> ('a,'b) endpoint -> unit
val eVM : vm -> (event -> unit) -> unit
val snapshotVM : vm -> vm_snapshot
val restoreVM : vm_snapshot -> unit
```

Em.mli

```
type tPayment = (Payment,string) endpoint
type tOrderEntry = (Order,string) endpoint
type tOrderProcessing = (Order,unit) endpoint
val createOrderEntryRole : tPayment -> tOrderProcessing -> (vm * tOrderEntry)
val createOrderProcessingRole : unit -> (vm * tOrderProcessing)
val createPaymentRole : unit -> (vm * tPayment)
val importPayment1 : unit -> tPayment
val importPayment2 : unit -> tPayment
val exportOrderEntry : tOrderEntry -> unit
```

Endpoints and Services

```
type Payment = { ... }
type Order = { ... }

type tOrderEntry = (Order,string) endpoint          // OrderEntry service
type tOrderProcessing = (Order,unit) endpoint       // OrderProcessing service
type tPayment = (Payment,string) endpoint           // Payment service
```

- A value of type (α,β) *endpoint* is the network address of a SOAP RPC server, reachable from VMs and the physical host
- (Only endpoints on the physical host are externally reachable)
- A service is (in general) a tuple of endpoints.
- The type of each service is an instance of the scheme:

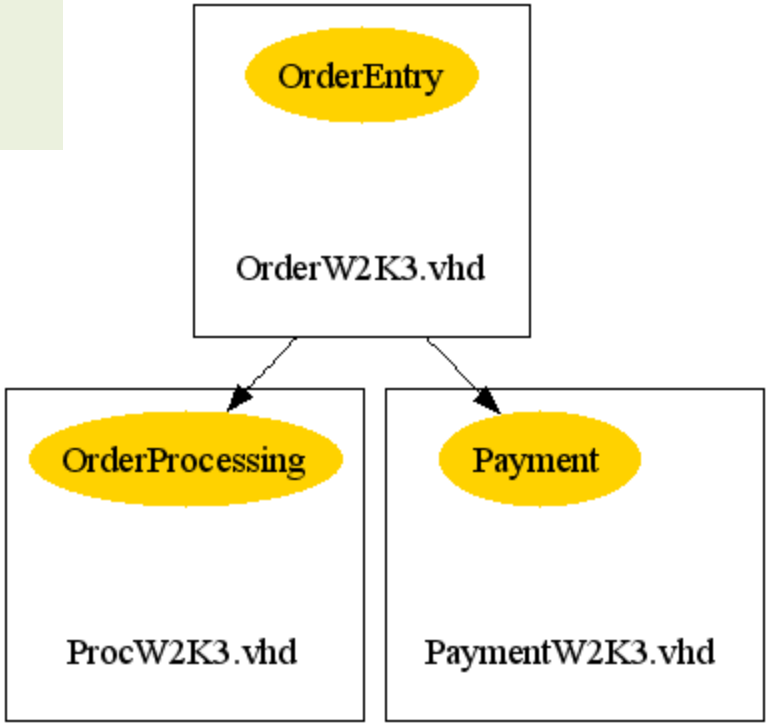
  (α_1,β_1) *endpoint* * ... * (α_n,β_n) *endpoint*

Disk Images as Typed Functions

```
val createOrderEntryRole : tPayment -> tOrderProcessing ->  (vm * tOrderEntry)
val createOrderProcessingRole : unit -> (vm * tOrderProcessing)
val createPaymentRole : unit -> (vm * tPayment)
```

```
let (vm1,e1) = createOrderProcessingRole ()
let (vm2,e2) = createPaymentRole ()
let (vm3,e3) = createOrderEntryRole e2 e1
```

- A value of type *vm* identifies a particular VM in the VMM
- VMs are booted from disk images held as physical files; the Baltic Server makes an RPC to the VM to set its imports (e2,e1) and get its exports (e3)

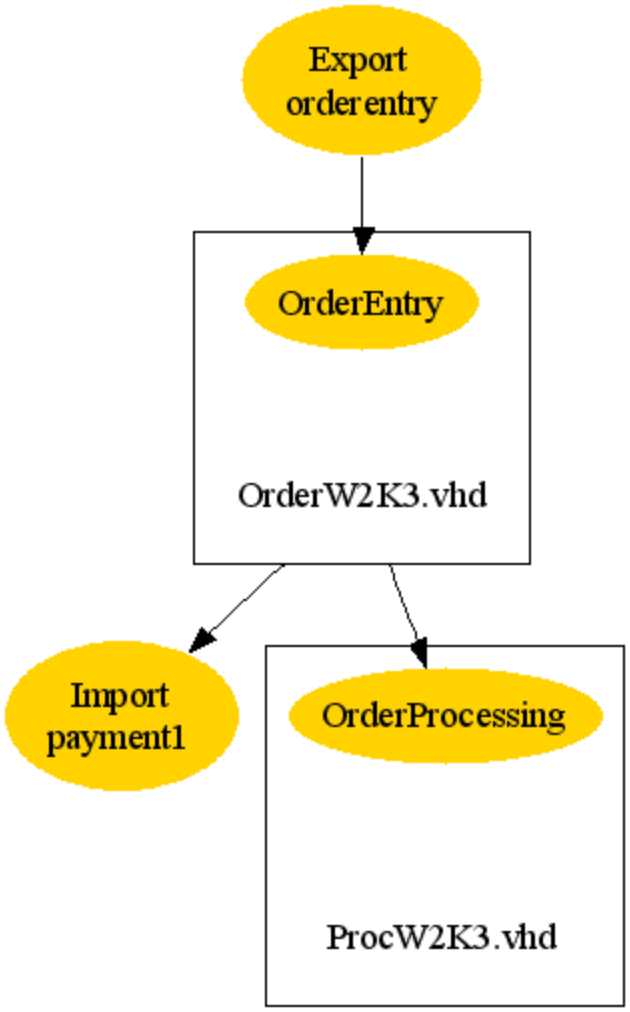


Import/Export as Typed Functions

```
val importPayment1 : unit -> tPayment
val importPayment2 : unit -> tPayment

val exportOrderEntry : tOrderEntry -> unit
```

```
let ei = importPayment1 ()
let (vm1,e1) = createOrderProcessingRole ()
let (vm2,e2) = createOrderEntryRole ei e1
let () = exportOrderEntry e2
```



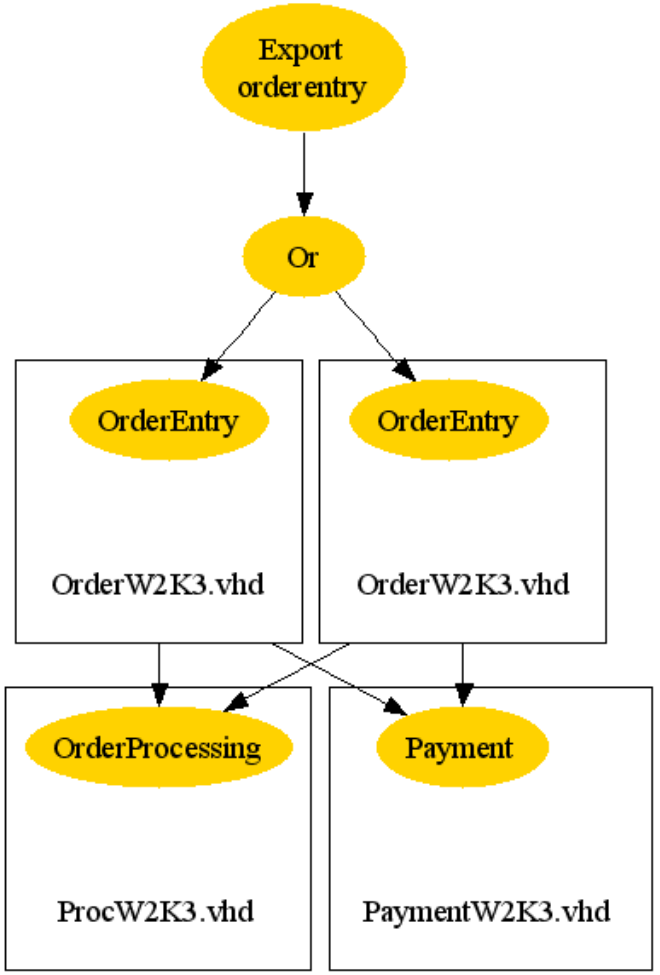
- Exporting or importing an endpoint creates a forwarder on the physical server
- The addressing details eg URLs are hidden by the API

An Intermediary for Load Balancing

val eOr : (α,β) endpoint -> (α,β) endpoint -> (α,β) endpoint

```
let (vm1,e1) = createOrderProcessingRole ()
let (vm2,e2) = createPaymentRole ()
let (vm3,e3) = createOrderEntryRole e2 e1
let (vm4,e4) = createOrderEntryRole e2 e1
let e34 = eOr e3 e4
let () = exportOrderEntry e34
```

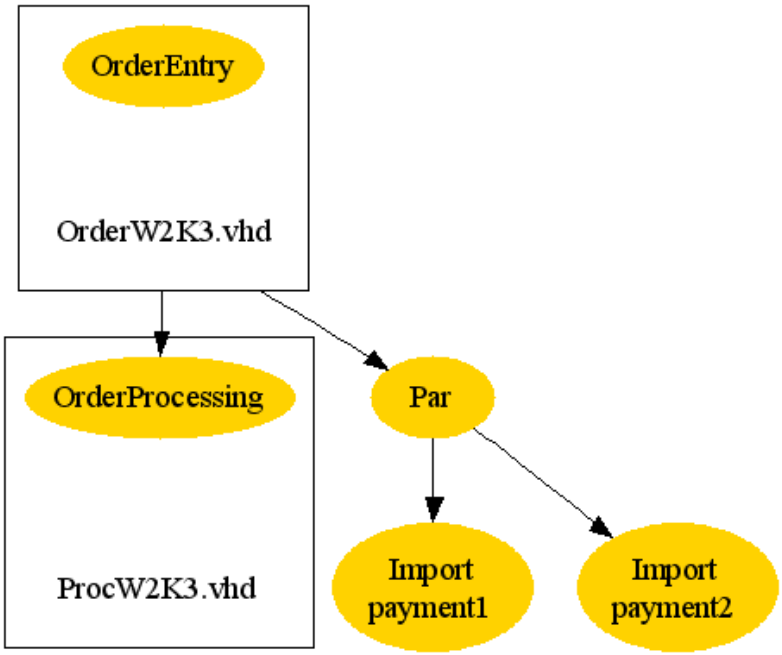
- We can utilize multiple processors by creating multiple instances of a role
- The Or-intermediary created by *eOr e3 e4* routes incoming requests to either *e3* or *e4*



An Intermediary for Fault Tolerance

val ePar: (α,β)endpoint -> (α,β)endpoint -> (α,β) endpoint

```
let e1 = importPayment1 ()
let e2 = importPayment2 ()
let e12 = ePar e1 e2
let (vm1,e3) = createOrderProcessingRole ()
let (vm3,e4) = createOrderEntryRole e12 e3
```

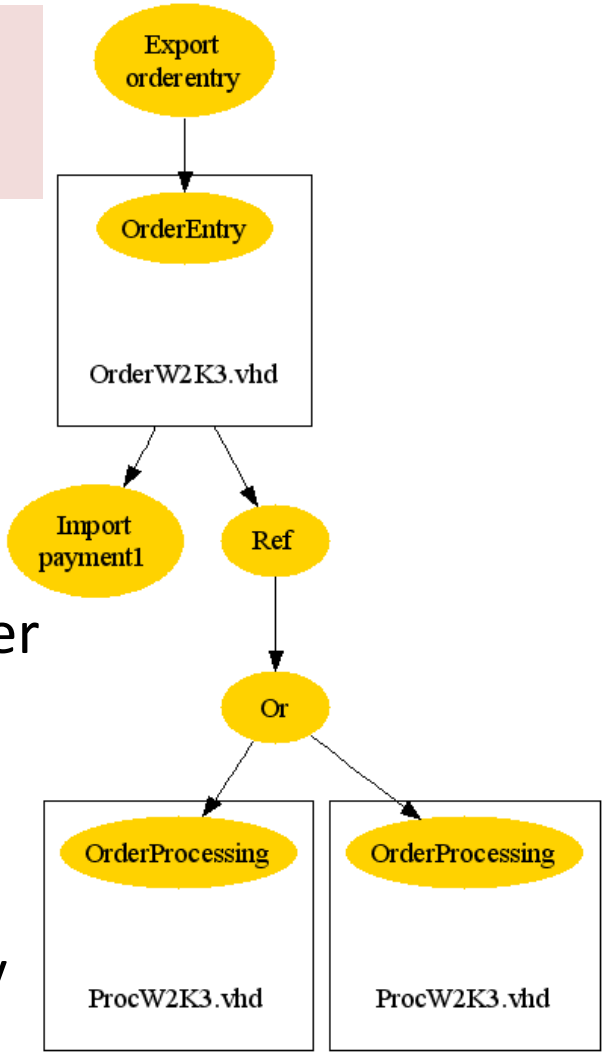


- The Par-intermediary created by *ePar e1 e2* routes incoming requests to both *e1* or e2; whichever returns first wins
- (Inspired by the service combinator *S1*|*S2* of Cardelli and Davies [1999])

An Intermediary for Dynamic Update

```
type (α,β) endpointref
val eRef : (α,β) endpoint -> (α,β )endpoint * (α,β) endpointref
val eRefUpdate : (α,β )endpointref -> (α,β) endpoint -> unit
```

```
...
let e3 = eOr e1 e2
let (e4,r) = eRef e3
let (vm5,e5) = createOrderEntryRole e0 e4
...
```

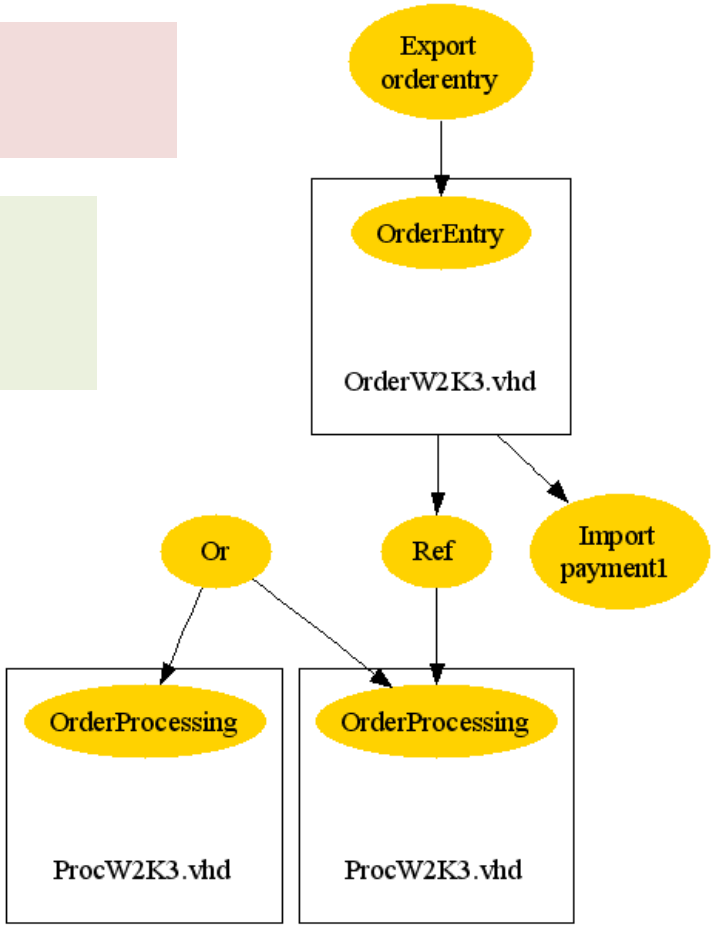


- A value of type *(α,β) endpointref* is a pointer to a Ref intermediary exporting an *(α,β) endpoint*
- The Ref-intermediary created by *eRef e3* forwards incoming requests to *e3*
- After *eRefUpdate r e'*, the Ref-intermediary forwards subsequent requests to *e'*

Event Handling

```
type event = VM_Crash
val eVM : vm -> (event -> unit) -> unit
```

```
let h e ev = match ev with VM_Crash -> eRefUpdate r e
let () =  Baltic.eVM vm1 (h e2)
let () =  Baltic.eVM vm2 (h e1)
```

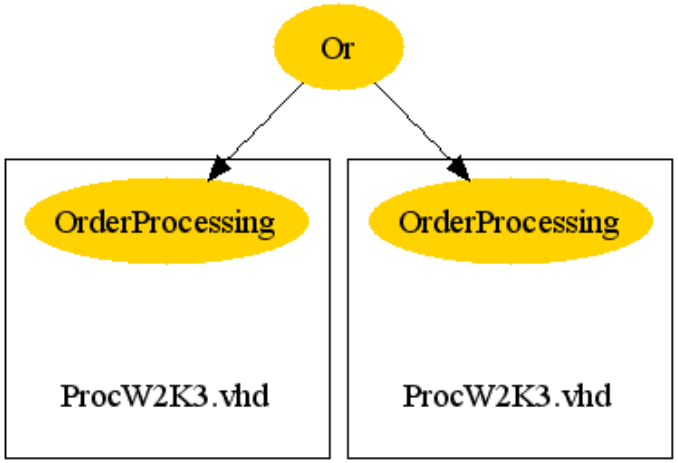


- VMMs detect many sorts of events, including VMs crashing
- *eVM vm h* installs *h* as a handler for events occurring on *vm*
- A current limitation is that we represent only the event *VM_Crash*

VM Snapshots

```
type vm_snapshot
val snapshotVM : vm -> vm_snapshot
val restoreVM : vm_snapshot -> unit
```

```
let svm1 = snapshotVM vm1
let svm2 = snapshotVM vm2
let h s ev = match ev with VM_Crash -> restoreVM s
let () =  eVM vm1 (h svm1)
let () =  eVM vm2 (h svm2)
```



- Some VMMs, including Virtual Server, allow snapshots of the current state of a VM and its virtual disks as physical files
- A value of type *vm_snapshot* is an identifier for such a state
- Using snapshots, we can revert a failed VM to a previous good state, faster than going through a reboot

MESSAGE SAFETY, TYPING, AND A FORMAL SEMANTICS

Baltic Scripts

- Given metadata *m*, let an *m*-script (a Baltic script) be a program that is well-typed given interfaces:
  - B.mli, the fixed part of the Baltic API; and
  - E*m*.mli, access to the roles and external endpoints in *m*.

- If we ensure Baltic scripts are well-formed by typechecking, we obtain a useful message safety property.
- An entity **respects** an endpoint of type (α,β) *endpoint* iff (1) each request sent by the entity to the endpoint has type α and (2) each response sent by the entity, in response to a request on the endpoint, has type β

Message Safety, by Typing

- **Message Safety Property (TBC)**: If
  - *m*-script S.ml passes typechecking, and
  - all remote entities respect the endpoints in *m*, and
  - disk images respect the endpoints they import and export

  then all entities arising during a run respect all endpoints.
- Many interconnection errors, where servers or intermediaries are connected to the wrong endpoints, lead to entities not respecting endpoints, that is, to requests or responses of unexpected types.
- These errors may arise at initial configuration, or sometime later, during reconnections.
- Our safety property guarantees, by static type-checking, that such errors cannot arise.

An Executable Formal Semantics

- Process calculi such as the pi-calculus are ideal for modelling highly-concurrent message-passing systems
- We build a process model of an *m*-script in two steps:
  - We implement the B.ml and E*m*.mli interfaces using concurrency primitives in an interface pi.mli, with (α,β) *endpoint* = $\alpha \rightarrow \beta$
  - We translate any program using just pi.mli into a process calculus (via a CPS transform followed by direct encoding)
- We prove that (1) well-typed programs map to well-typed processes, and (2) process computation preserves typings.
- Hence, we can formalize the type safety result (TBC!)
- To model multiple VMs, processes look like: $a_1[P_1] | ... | a_n[P_n]$
- To model snapshots, we allow partitions $[P]$ as values.

A Concurrent ML

pi.mli

```
type 'a chan                        // channel holding messages of type ‘a
type name                           // identifier
type part                           // partition [P]

val chan: string -> 'a chan         // create fresh channel
val send: 'a chan -> 'a -> unit     // send message on channel
val recv: 'a chan -> 'a             // receive message off channel
val fork: (unit -> unit) -> unit    // start thread in parallel
val name: string -> name            // create fresh name
val box: (unit -> unit) -> part     // create new partition
val start: name -> part -> unit     // start named partition
val stop: name -> part              // stop named partition
```

RELATED WORK AND CONCLUSIONS

Related Systems

- Edinburgh LCFG [Anderson 94] – scripting language to control large scale UNIX installations – shows farm management can be seen as a pure programming problem
- HP SmartFrog [Goldsack et al 03] – DSL to describe server components – typed, but not based on typed endpoints
- SDM/SML [MSFT 05] – XML formats for describing data centre components – not a programming language, but shows industry move towards explicit metadata for server farms
- Whitehorse [MSFT 05] – Distributed System Designers with both physical and logical views – visual notation, static topologies
- AppLogic [3Tera, 06] – AJAX visual designer for virtualized server farms – untyped scripting
- In the Singularity OS [Hunt, Larus, et al], typed message-passing is the sole means of interprocess communication. Disk images constructed using Singularity could be checked to conform to Baltic's assumptions

Conclusions

- We have described a set of combinators for assembling networks of virtual machines.
- A combination of type checking together with automated allocation of addresses prevents the troublesome configuration errors that may arise with alternatives, such as untyped scripts.
- There is a semantics based on a pi-calculus with partitions and an implementation using Virtual Server with scripts in F#.

- Virtualization technology makes possible the automatic assembly of Big Components like DBs and OSs into systems
- An API like Baltic is a way to exploit this possibility in a typeful and declarative style

THE END