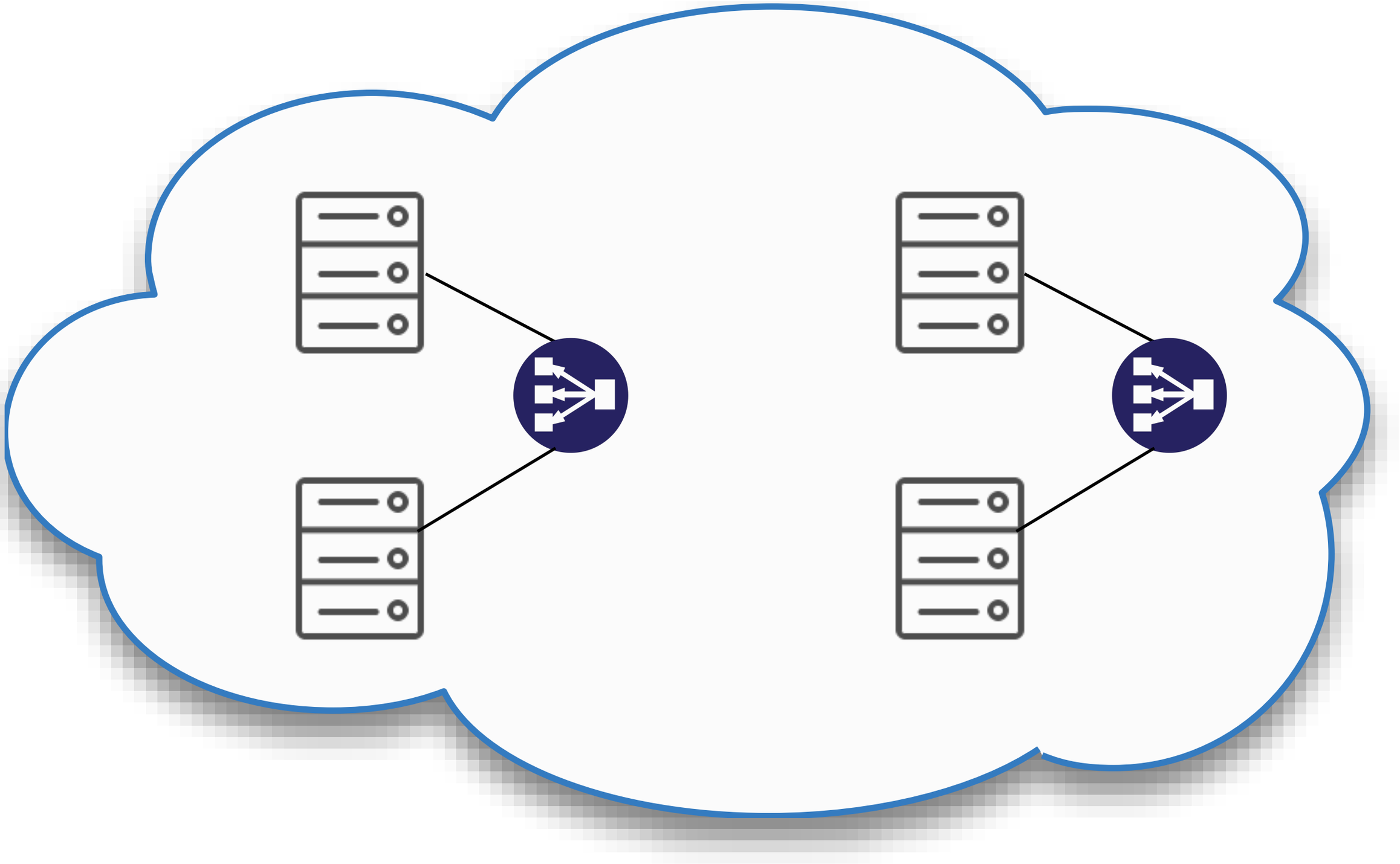
CPL: A Core Language for Cloud Computing

Oliver Bračevac
Sebastian Erdweg
Guido Salvaneschi
Mira Mezini

TECHNISCHE UNIVERSITÄT DARMSTADT
SOFTWARE TECHNOLOGY GROUP

Deployment in the Cloud

Deployment in the Cloud



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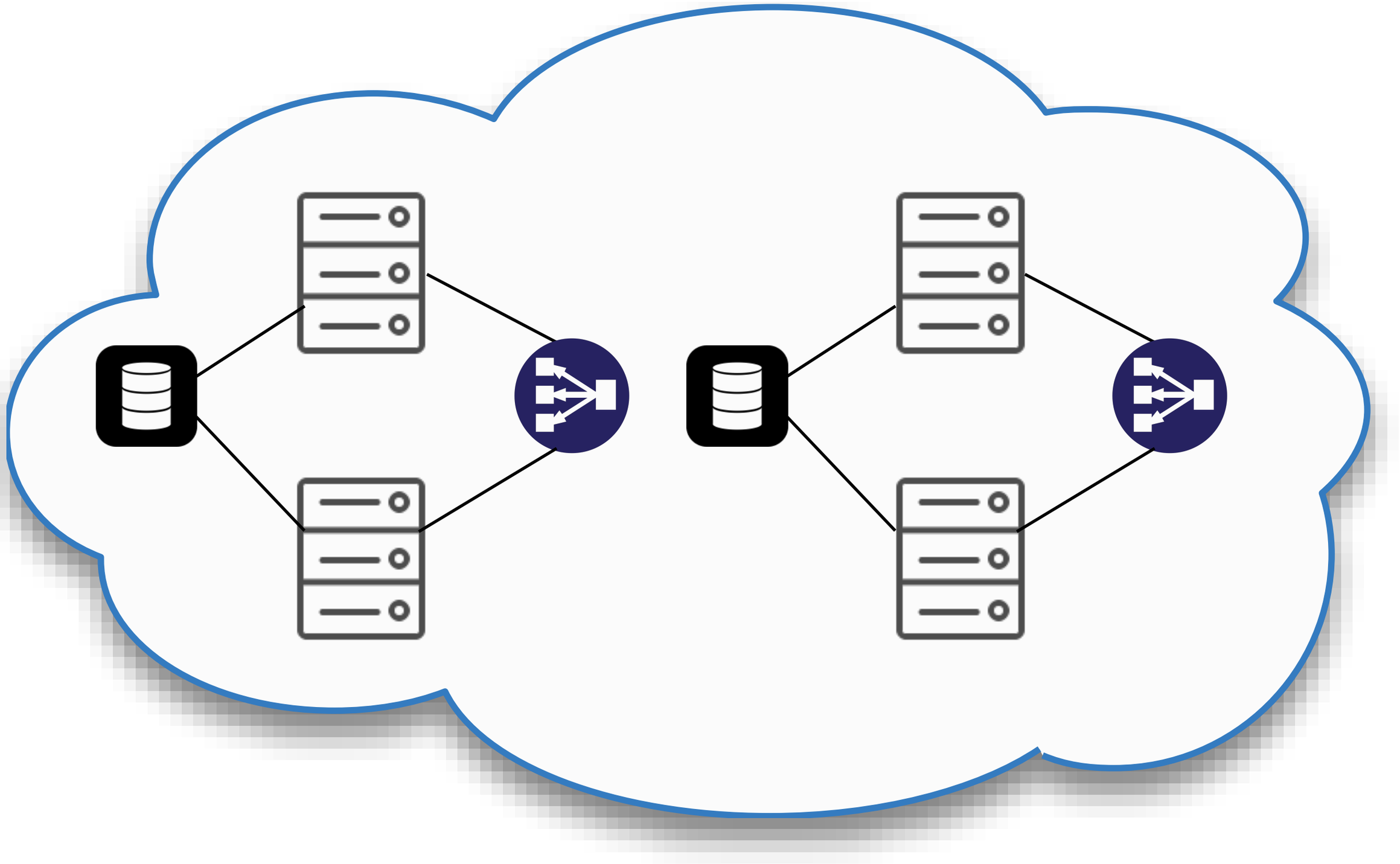

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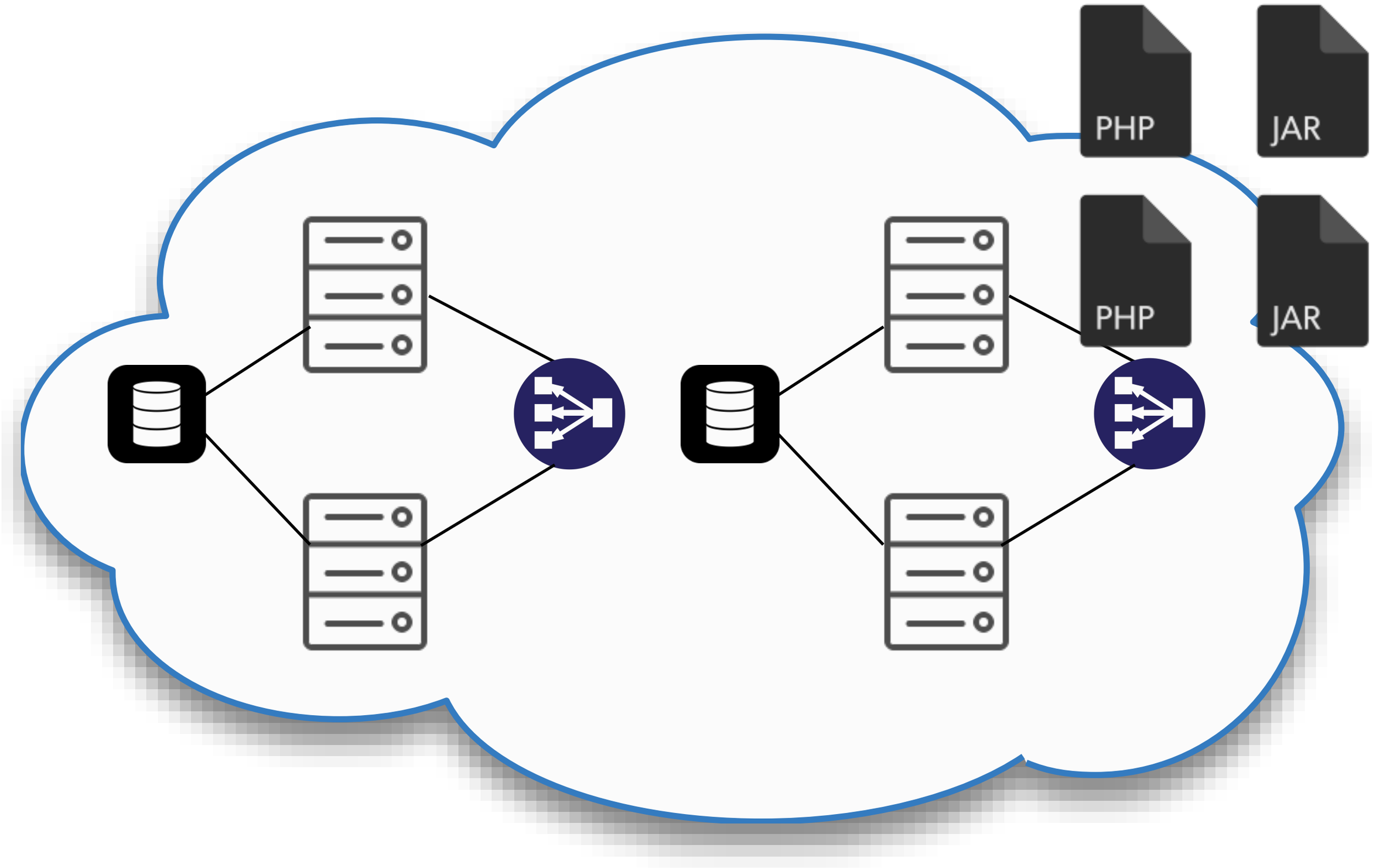

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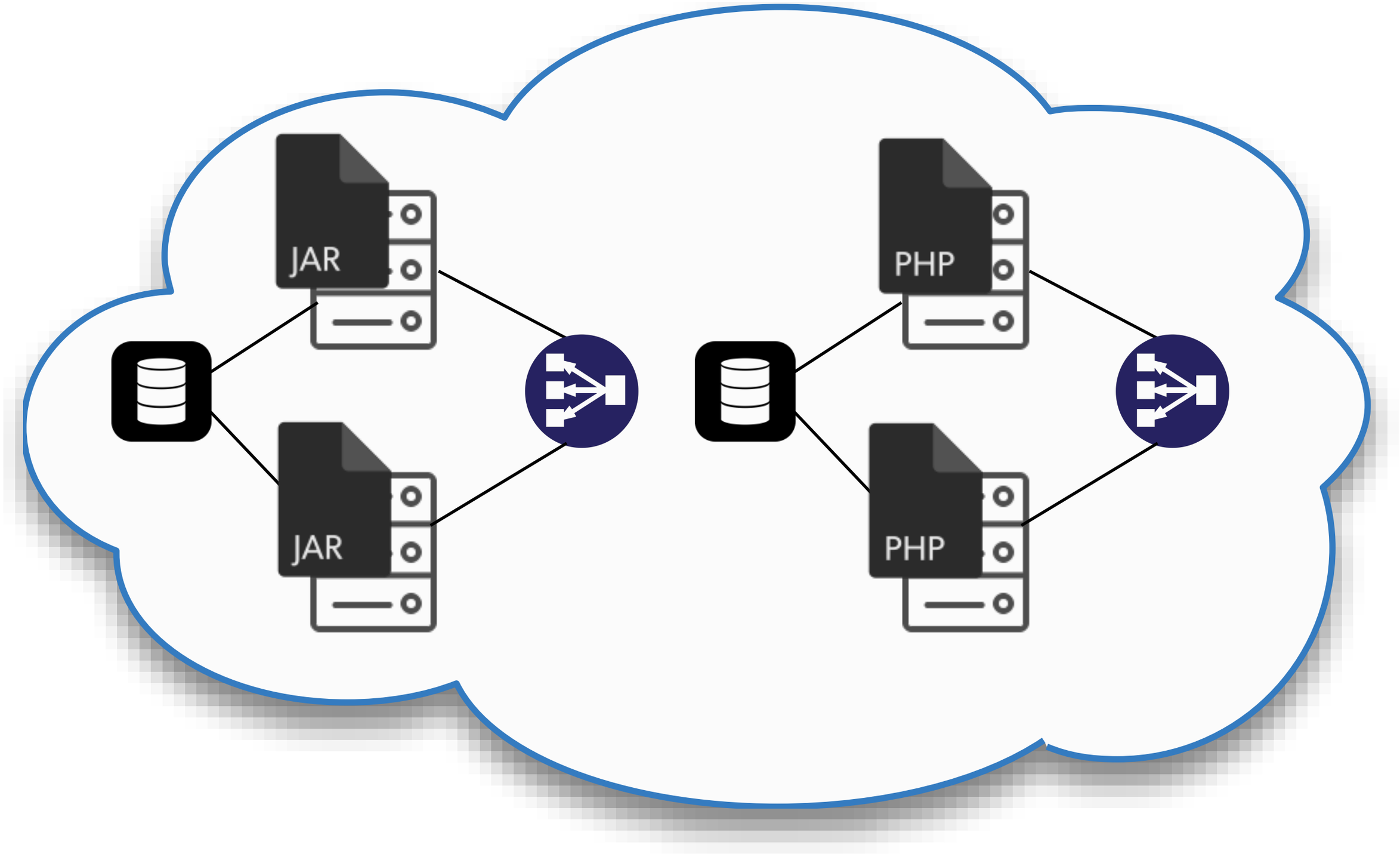

Deployment in the Cloud

Specify Deployment Patterns with modular DSLs


```
{ //...
  "Parameters" : {
    "InstanceType" : {
      "Description" : "WebServer EC2 instance type",
      "Type" : "String",
      "Default" : "t2.small",
      "AllowedValues" : [ "t2.micro", "t2.small",
      "ConstraintDescription" : "must be a valid EC2 instance type."
    }  //...
  },
  "Resources" : {
    "WebServer": {
      "Type" : "AWS::EC2::Instance",
      "Properties": {
        "InstanceType"   : { "Ref" : "InstanceType" },
        "UserData" : { "Fn::Base64" : { "Fn::Join" : ["", [
                    "#!/bin/bash -xe\n",
                    "yum update -y aws-cfn-bootstrap\n",

                    "/opt/aws/bin/cfn-init -v ",
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                    "      --resource WebServer ",
                    "      --configsets wordpress_install ",
                    "      --region ", { "Ref" : "AWS::Region" },"\n"
        ]]}}, //...
      },
    }
  },
  "Outputs" : {
    "WebsiteURL" : {
      "Value" : { "Fn::Join" : ["", ["http://", { "Fn::GetAtt" :
[ "WebServer", "PublicDnsName" ]}, "/wordpress" ]]},
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```

Deployment in the Cloud

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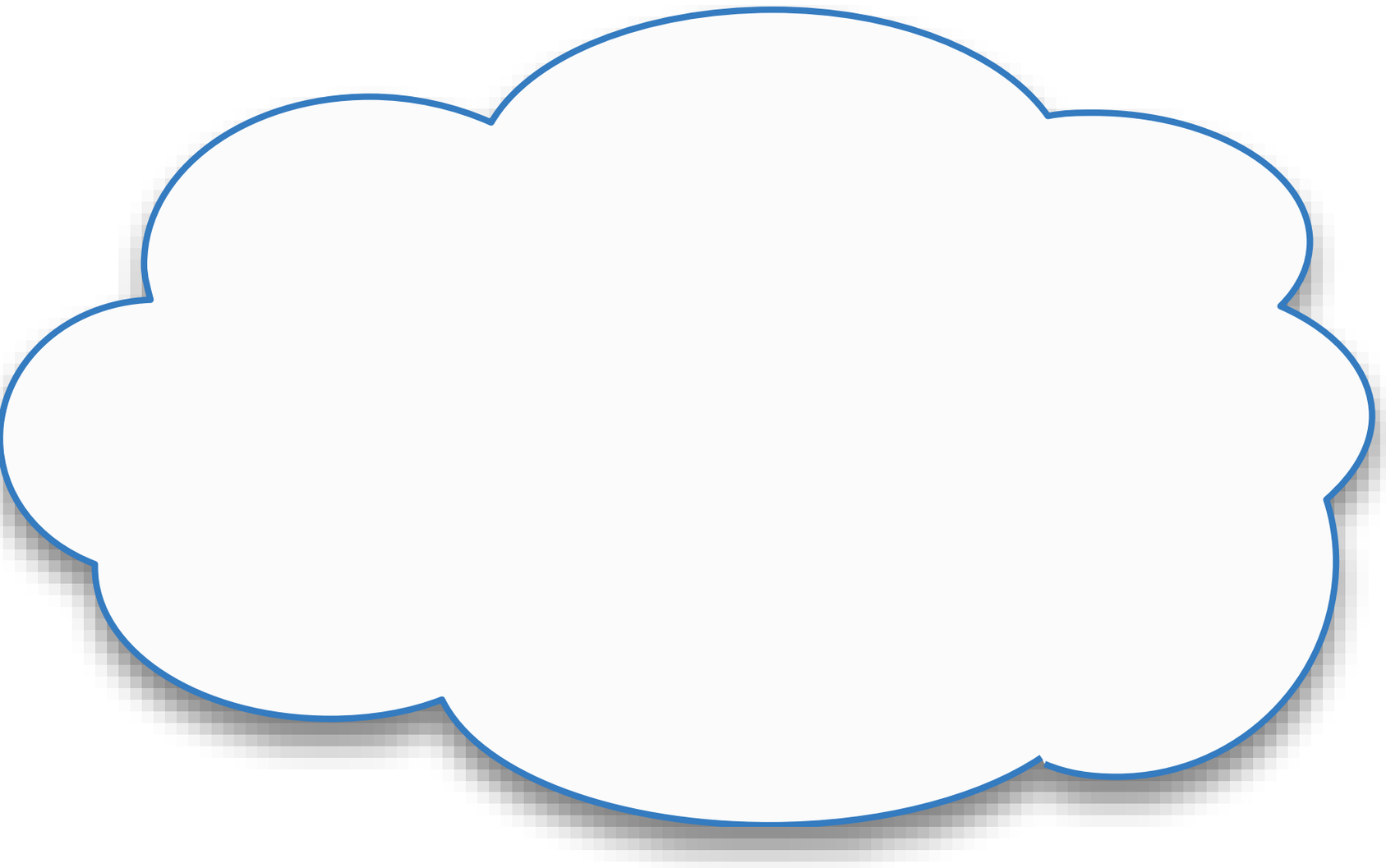

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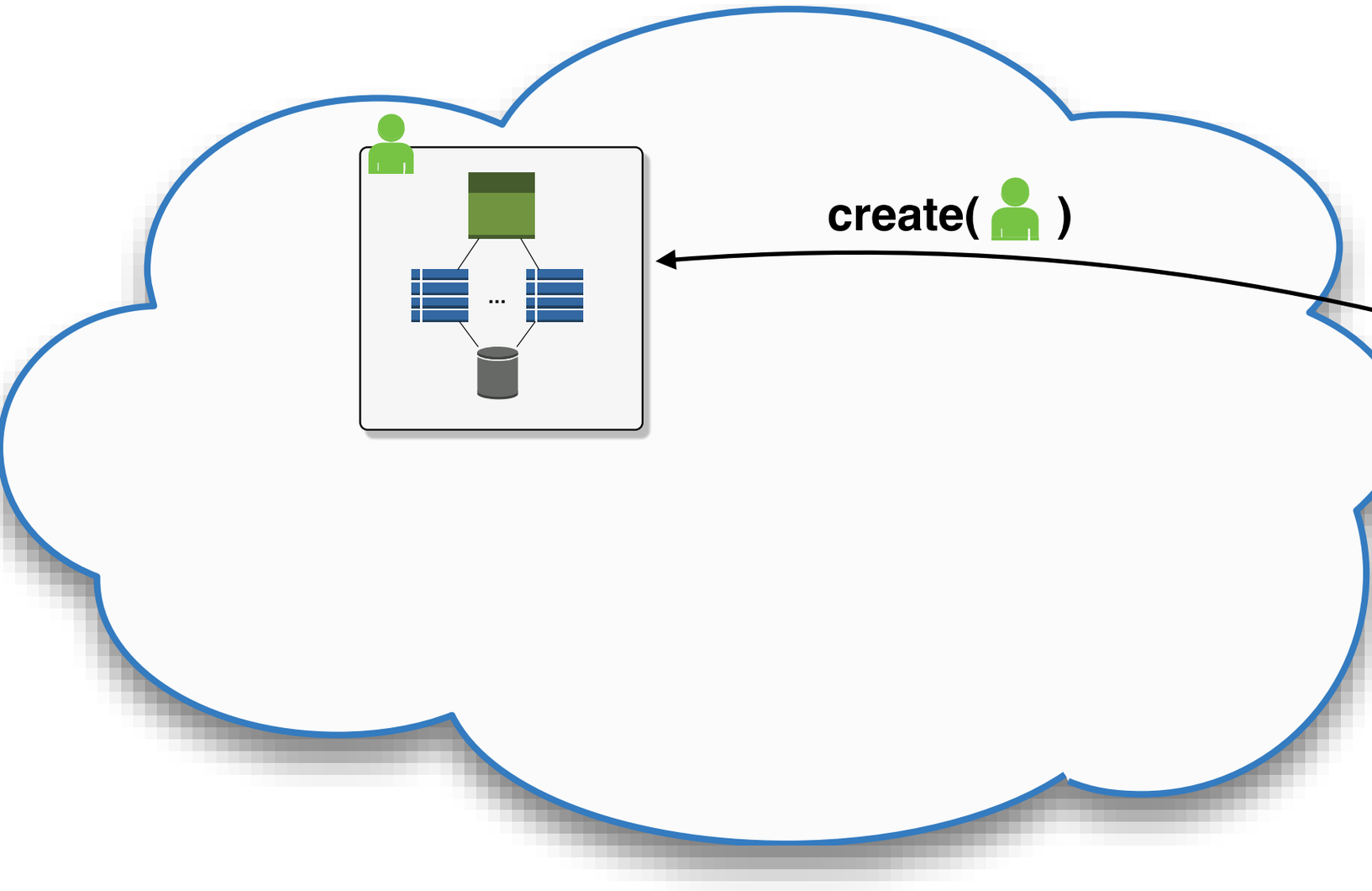


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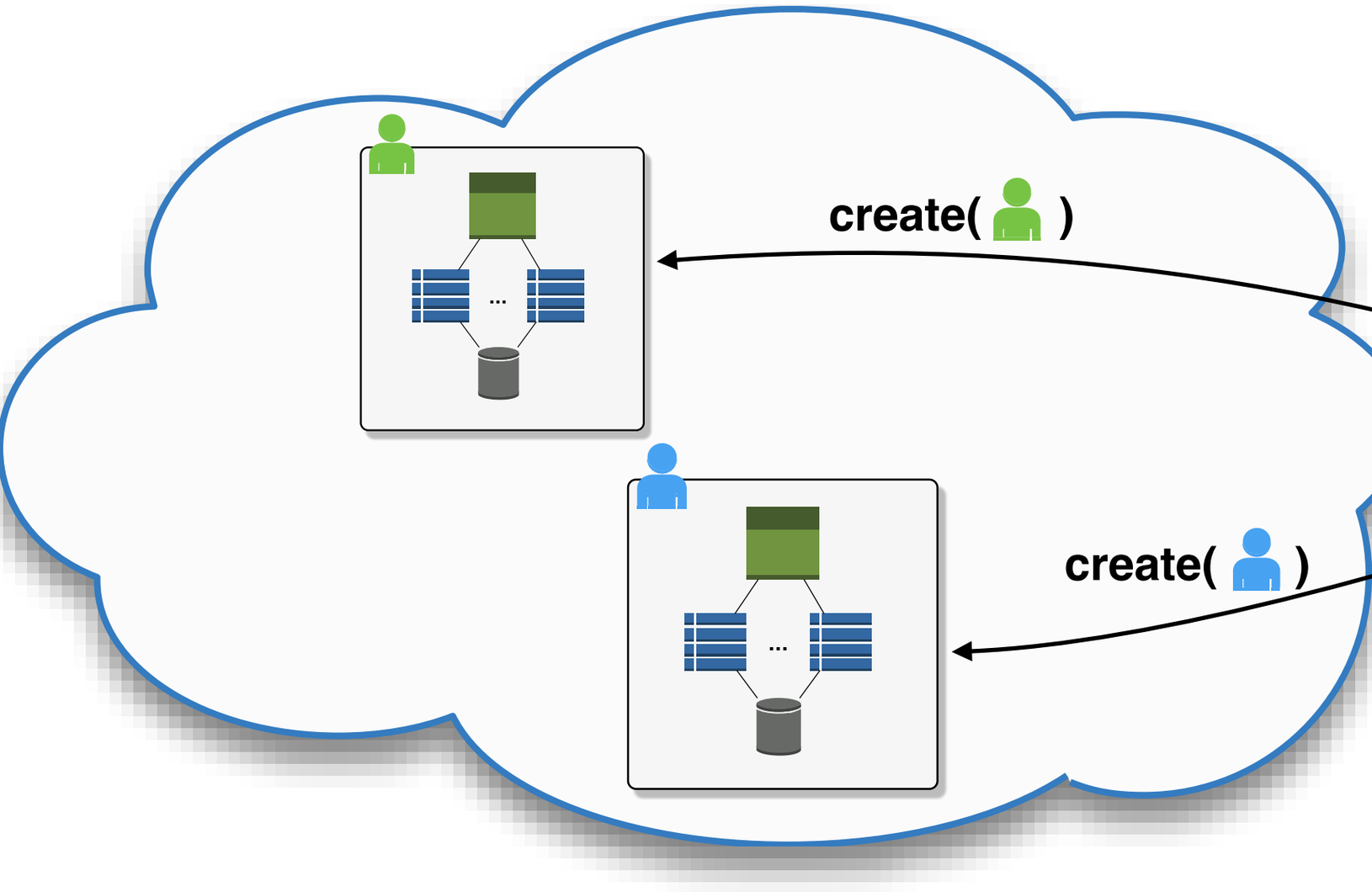


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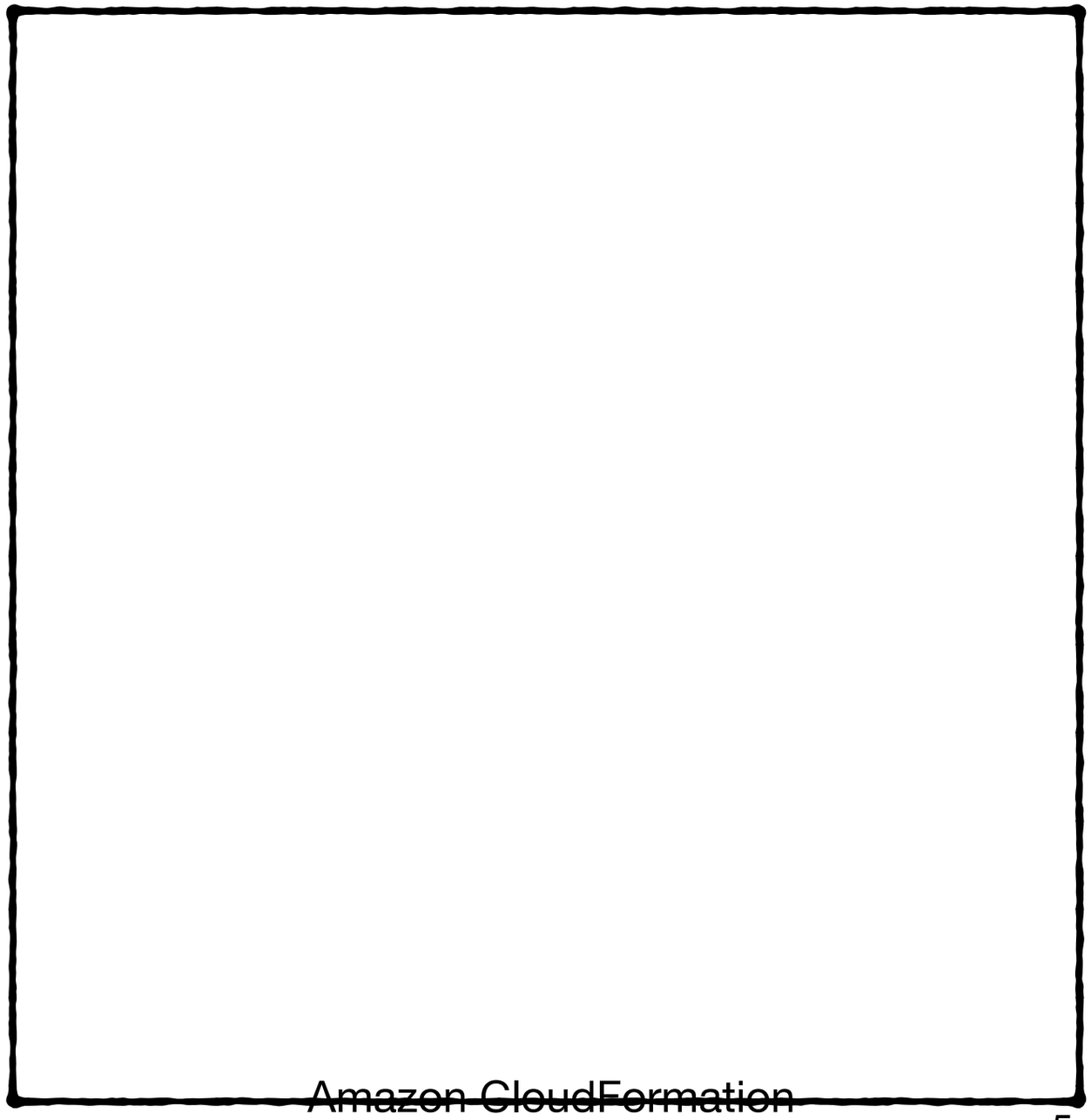
Deployment DSLs

Anatomy of Templates



Deployment DSLs

Anatomy of Templates

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Deployment DSLs

Anatomy of Templates

- Parameters
- Resource Specifications

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    "AllowedValues" : ["t2.micro", "t2.small"]
  } //...
},
"Resources" : {
  "WebServer": {
    "Type" : "AWS::EC2::Instance",
    "Properties": { ... },
  }
  "ElasticLoadBalancer" : {
   "Type":"AWS::ElasticLoadBalancing::LoadBalancer",
   "Properties" : { ... }
  }
},
```

Amazon CloudFormation

Deployment DSLs

Anatomy of Templates

- Parameters
- Resource Specifications
- Output

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    [ "WebServer", "PublicDnsName" ]}, "/wordpress" ]]}}}
```

Deployment DSLs

Unsafe Parameterization

```
"files" : {
  "/var/www/php/index.php" : {
     "content" : {"Fn::Join" : [ "", [
       "<html>\n",
          "<head>\n",
            "</head>\n",
          "<body>\n",
            "<?php ", {"Ref" : "SetupFunction"}, "(); ?>\n",
          "</body>\n",
       "</html>\n" ]]},
  "mode" : "000500",
  "owner" : "root",
  "group" : "root"
  }
}
```

Deployment DSLs

Two-phase Staging: Indirect topology changes at run time

Deploy → Run

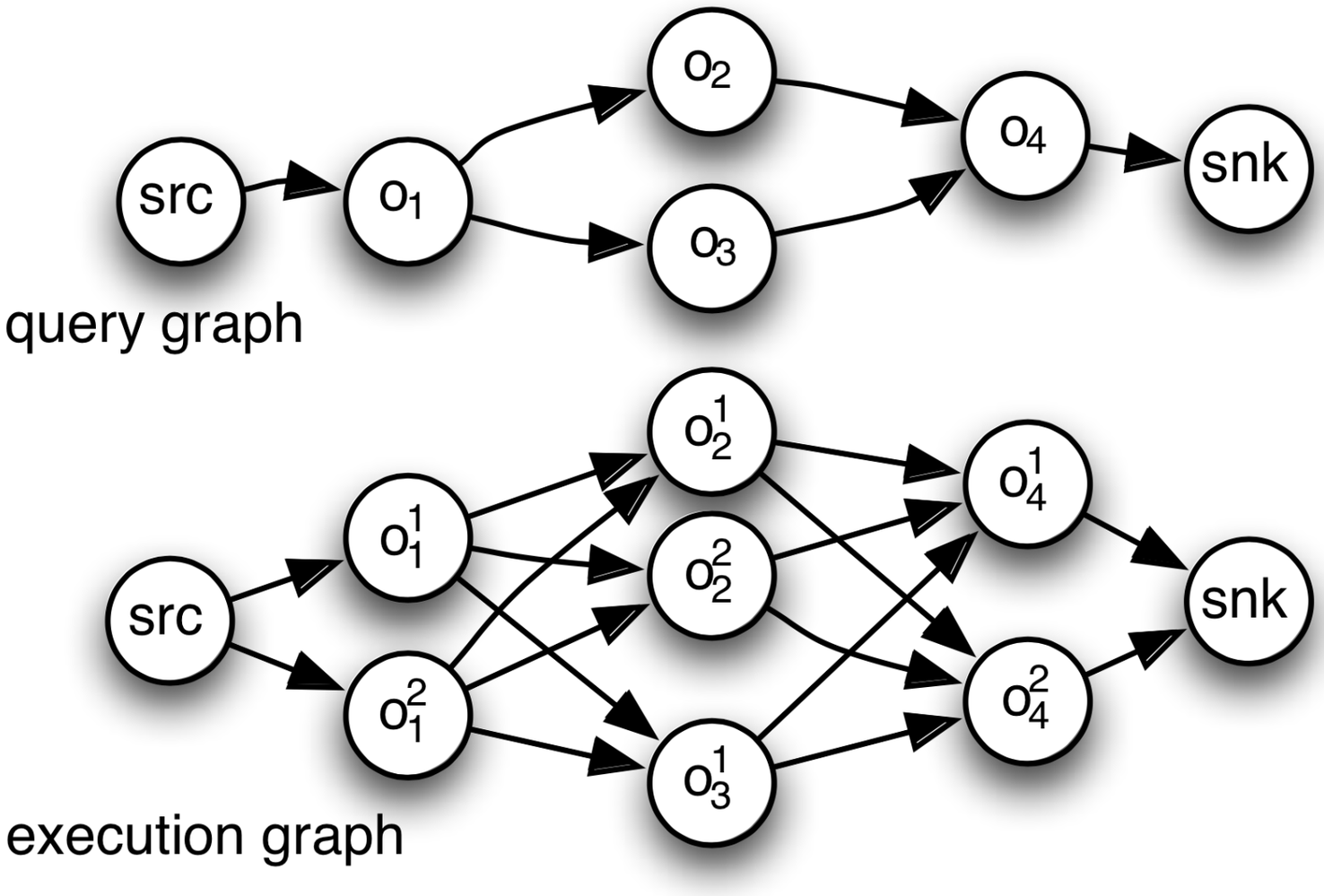


Image taken from [Fernandez et al. ’13]

Deployment DSLs

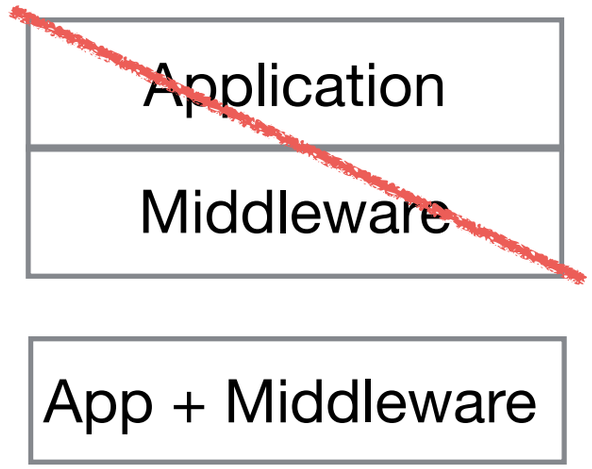
Inextensible Middleware Services

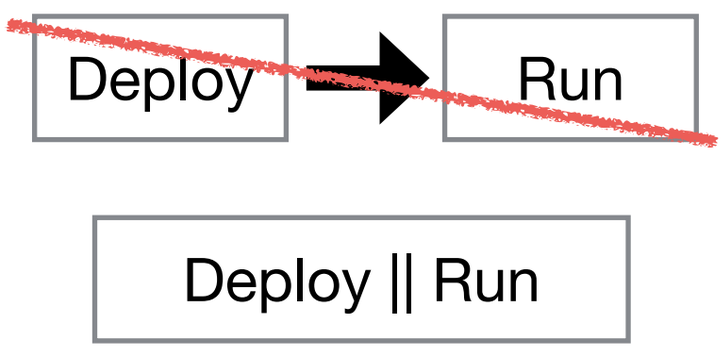
```
"ElasticLoadBalancer" : {
  "Type" : "AWS::ElasticLoadBalancing::LoadBalancer",
  "Properties" : {
    "Instances" : [ {"Ref":"Ec2Instance1"},{"Ref":"Ec2Instance2"} ],
    "Listeners" : [ {
      "LoadBalancerPort" : "80",
      "InstancePort" : {"Ref":"WebServerPort"},
      "Protocol" : "HTTP"
    } ],
   ...
 }
}
```

The Cloud Platform Language

A core language for reasoning & studying

- Distributed cloud applications
- Programmable, extensible middleware
- Safe service composition
- Dynamic deployment





First-class Servers

$$
\begin{array}{l}
\texttt{Fib} = \mathbf{srv}\ \{ \\
\quad \texttt{fib}\langle n,\ k\rangle \ \triangleright\ \mathbf{this}\sharp\texttt{acc}\langle n, \texttt{0}, \texttt{1}, k\rangle \\
\\
\quad \texttt{acc}\langle n,\ a,\ b,\ k\rangle\ \triangleright \\
\qquad \mathbf{if}\ n = \texttt{0} \\
\qquad \mathbf{then}\ k\langle a\rangle \\
\qquad \mathbf{else}\ \ \mathbf{this}\sharp\texttt{acc}\langle n - \texttt{1},\ b,\ a + b,\ k\rangle \\
\}
\end{array}
$$

$$
(\mathbf{spwn}\ \texttt{Fib})\sharp\texttt{fib}\langle \texttt{10},k\rangle \longrightarrow i\sharp\texttt{fib}\langle \texttt{10},k\rangle \longrightarrow i\sharp\texttt{acc}\langle \texttt{10},\texttt{0},\texttt{1},k\rangle \longrightarrow^{*} k\langle \texttt{55}\rangle
$$

First-class Servers

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\}
\end{array}
$$

Server Template

$$(\mathbf{spwn}\ \texttt{Fib})\sharp\texttt{fib}\langle 10,k\rangle \longrightarrow i\sharp\texttt{fib}\langle 10,k\rangle \longrightarrow i\sharp\texttt{acc}\langle 10,0,1,k\rangle \longrightarrow^* k\langle 55\rangle$$

First-class Servers

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Server Template

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Cloud spawns server instances from templates

Message Passing & CPS

```
Fib2 = srv {
   fib⟨n, k⟩ ▷
      if n = 0 ∨ n = 1
         k⟨n⟩
      else letk x = this♯fib⟨n − 1⟩
           in letk y = this♯fib⟨n − 2⟩
              in k⟨x + y⟩
}
```

Message Passing & CPS

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Fib2 = srv {
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Direct style program

Message Passing & CPS

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            in k⟨x + y⟩
}
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Direct style program

Desugaring:

$$\textbf{letk}\ x = e_1\langle \overline{e} \rangle\ \textbf{in}\ e_2 \quad \rightsquigarrow \quad e_1\langle \overline{e}, (\textbf{spwn}\ (\textbf{srv}\ \mathtt{k}\langle x \rangle \triangleright e_2))\sharp \mathtt{k} \rangle$$

Message Passing & CPS

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Fib2 = srv {
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Direct style program

Desugaring:

Callback to server

$$\textbf{letk}\ x = e_1\langle \overline{e} \rangle\ \textbf{in}\ e_2 \quad \rightsquigarrow \quad e_1\langle \overline{e}, (\textbf{spwn}\ (\textbf{srv}\ \mathtt{k}\langle x \rangle \triangleright e_2))\sharp \mathtt{k} \rangle$$

There is only async message passing!

Message Passing & CPS

Service Composition

```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    cache♯lookup⟨n, k, this♯run⟩
  run⟨n,k⟩ ▷
    if n = 0 ∨ n = 1
    then k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
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```
Memo = srv {
  lookup⟨n, k_hit, k_miss⟩ ▷
    if hasEntry(n)
    then k_hit⟨get(n)⟩
    else letk v = k_miss⟨n⟩
           in put(n, v);
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  // details omitted ...
}
```

Message Passing & CPS

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```
let cache = (spwn Memo) in (spwn Fib2)♯fib⟨10,k⟩
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Message Passing & CPS

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  fib⟨n, k⟩ ▷
    cache♯lookup⟨n, k, this♯run⟩

  run⟨n,k⟩ ▷
    if n = 0 ∨ n = 1
    then k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
           in letk y = this♯fib⟨n − 2⟩
                in k⟨x + y⟩
}

Memo = srv {
  lookup⟨n, k_hit, k_miss⟩ ▷
    if hasEntry(n)
    then k_hit⟨get(n)⟩
    else letk v = k_miss⟨n⟩
           in put(n, v);
              k_hit⟨v⟩

  // details omitted ...
}

let cache = (spwn Memo) in (spwn Fib2)♯fib⟨10,k⟩
```

Message Passing & CPS

Service Composition

```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    cache♯lookup⟨n, k, this♯run⟩

  run⟨n,k⟩ ▷
    if n = 0 ∨ n = 1
    then k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
           in letk y = this♯fib⟨n − 2⟩
                in k⟨x + y⟩
}

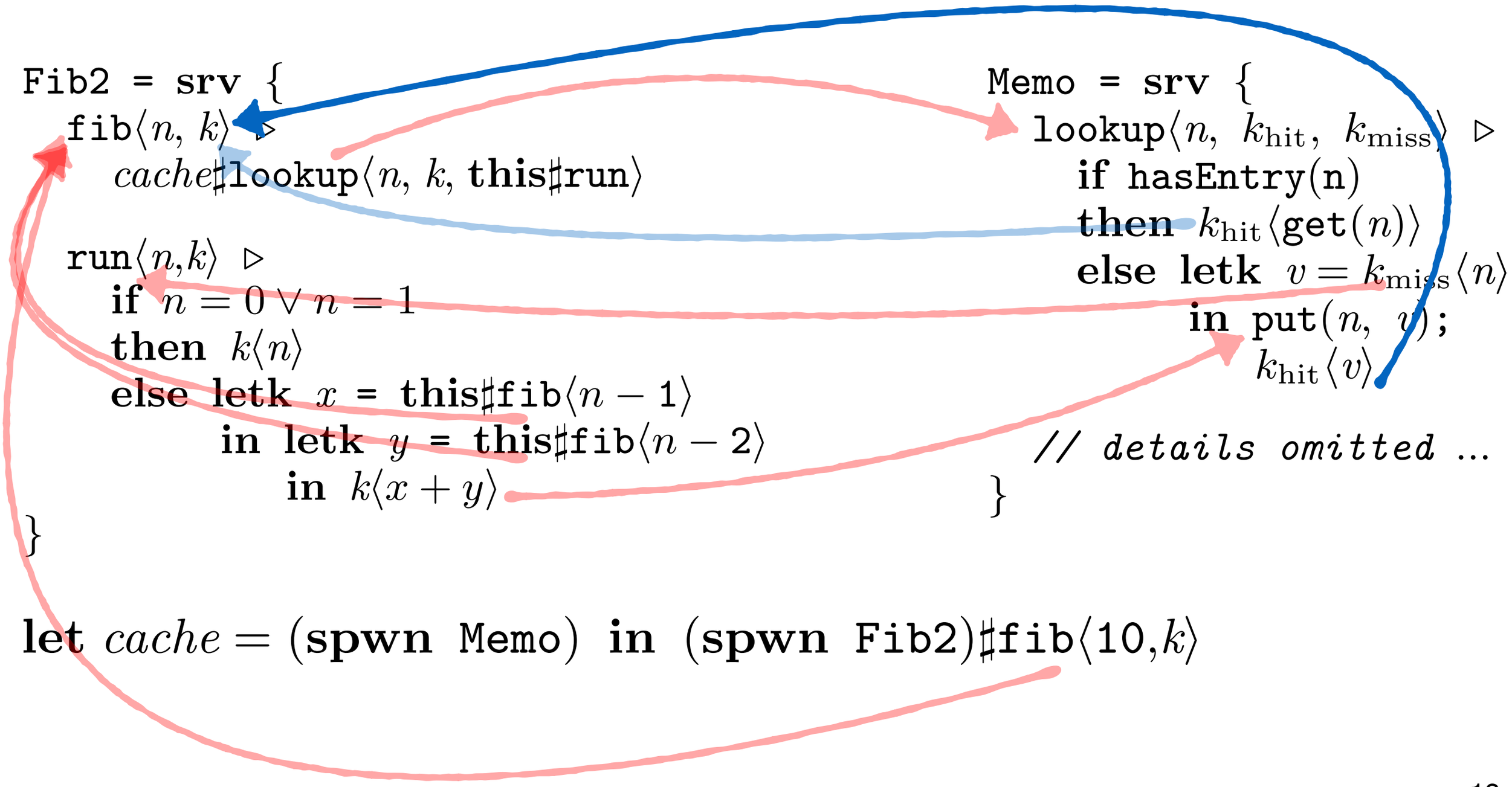
Memo = srv {
  lookup⟨n, k_hit, k_miss⟩ ▷
    if hasEntry(n)
    then k_hit⟨get(n)⟩
    else letk v = k_miss⟨n⟩
           in put(n, v);
              k_hit⟨v⟩

  // details omitted ...
}

let cache = (spwn Memo) in (spwn Fib2)♯fib⟨10,k⟩
```

Message Passing & CPS

Service Composition



Concurrency & Join Patterns

[Fournet and Gonthier ’96, Turon and Russo ‘11]

```
Fib3 = srv {
  fib⟨n, k⟩ ▷
    this♯caller⟨k⟩ ‖ this♯invoke⟨n⟩

  invoke⟨n⟩ ▷
    if n = 0 ∨ n = 1
       this♯res⟨n⟩
    else   (spwn Fib3)♯fib⟨n − 1, this♯left⟩
         ‖(spwn Fib3)♯fib⟨n − 2, this♯right⟩

  left⟨n⟩ & right⟨m⟩ ▷
    this♯res⟨n + m⟩

  res⟨n⟩ & caller⟨k⟩ ▷ k⟨n⟩
}
```

Concurrency & Join Patterns

[Fournet and Gonthier ’96, Turon and Russo ‘11]

```
Fib3 = srv {
  fib⟨n, k⟩ ▷
    this♯caller⟨k⟩ ‖ this♯invoke⟨n⟩

  invoke⟨n⟩ ▷
    if n = 0 ∨ n = 1
      this♯res⟨n⟩
    else (spwn Fib3)♯fib⟨n − 1, this♯left⟩
       ‖(spwn Fib3)♯fib⟨n − 2, this♯right⟩

  left⟨n⟩ & right⟨m⟩ ▷
    this♯res⟨n + m⟩

  res⟨n⟩ & caller⟨k⟩ ▷ k⟨n⟩
}
```

Parallel execution

Concurrency & Join Patterns

[Fournet and Gonthier '96, Turon and Russo '11]

```
Fib3 = srv {
  fib⟨n, k⟩ ▷
    this♯caller⟨k⟩ ‖ this♯invoke⟨n⟩

  invoke⟨n⟩ ▷
    if n = 0 ∨ n = 1
      this♯res⟨n⟩
    else (spwn Fib3)♯fib⟨n − 1, this♯left⟩
       ‖(spwn Fib3)♯fib⟨n − 2, this♯right⟩

  left⟨n⟩ & right⟨m⟩ ▷
    this♯res⟨n + m⟩

  res⟨n⟩ & caller⟨k⟩ ▷ k⟨n⟩
}
```

Parallel execution

Joins for synchronization

Server Management

```
Migratable = srv {
  migrate⟨dest⟩ ▷
    let img = snap this
    in (dest⟨img⟩
        ‖ repl this 0)

  // ...
}
```

Server Management

```
Migratable = srv {
  migrate⟨dest⟩ ▷
    let img = snap this
    in (dest⟨img⟩
        ‖ repl this 0)

  // ...
}
```

Retrieve server image from cloud

Server Management

```
Migratable = srv {
  migrate⟨dest⟩ ▷
    let img = snap this
    in (dest⟨img⟩
        ‖ repl this 0)
  // ...
}
```

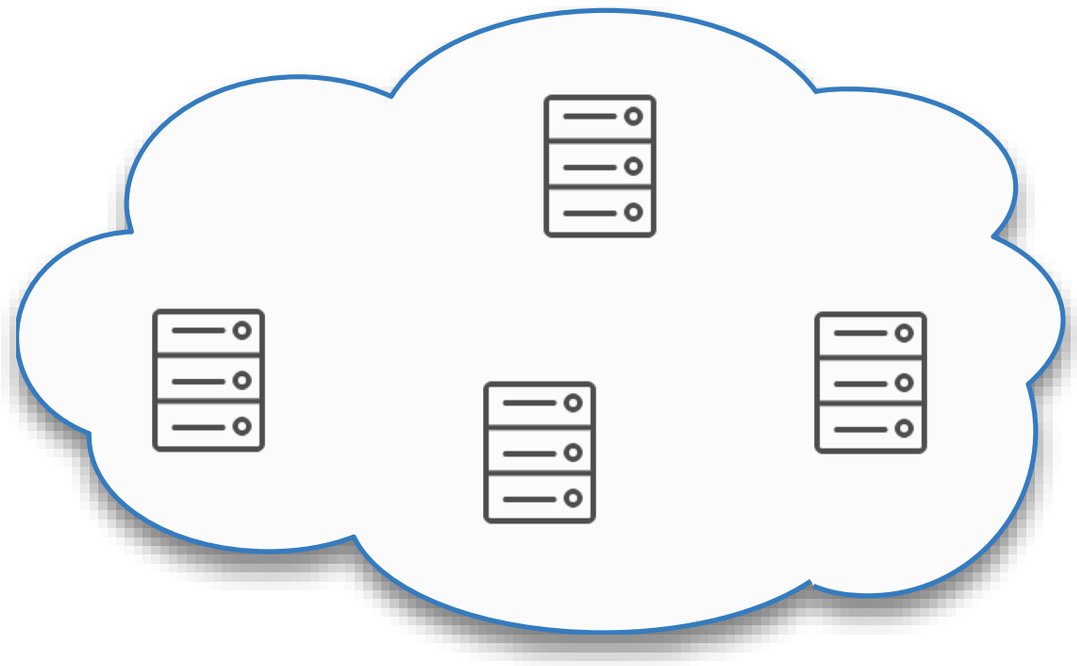
Retrieve server image from cloud

Replace with different image (inactive server in this case)

Server Placement

Are First-Class Servers VMs?

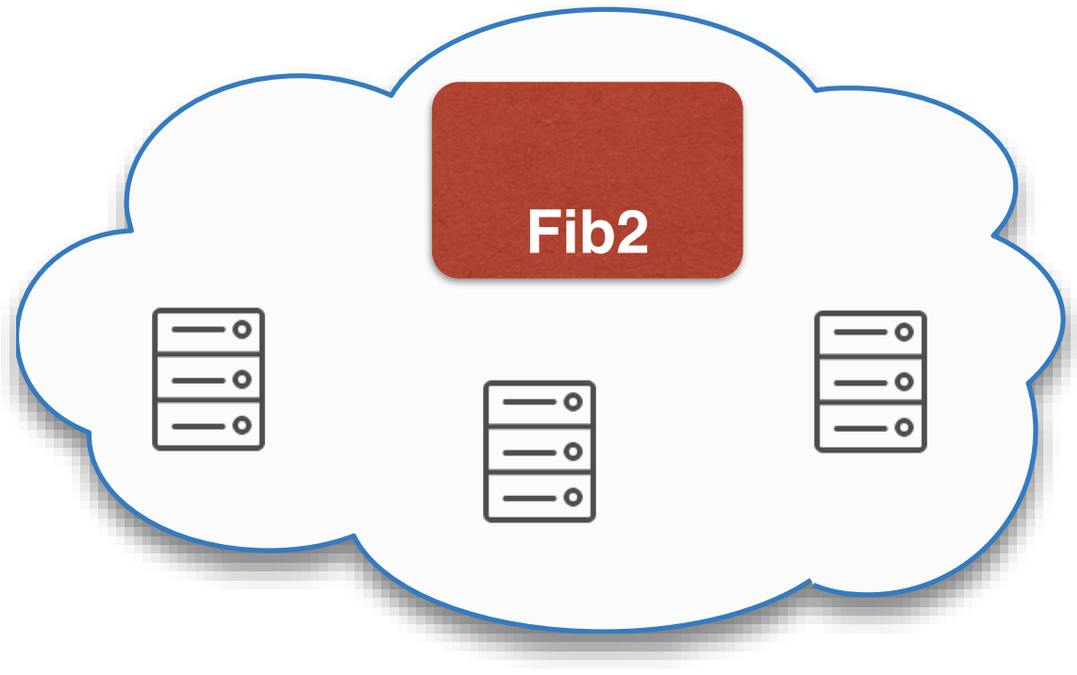
```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    if n = 0 ∨ n = 1
      k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
         in letk y = this♯fib⟨n − 2⟩
            in k⟨x + y⟩
}
```



Server Placement

Are First-Class Servers VMs?

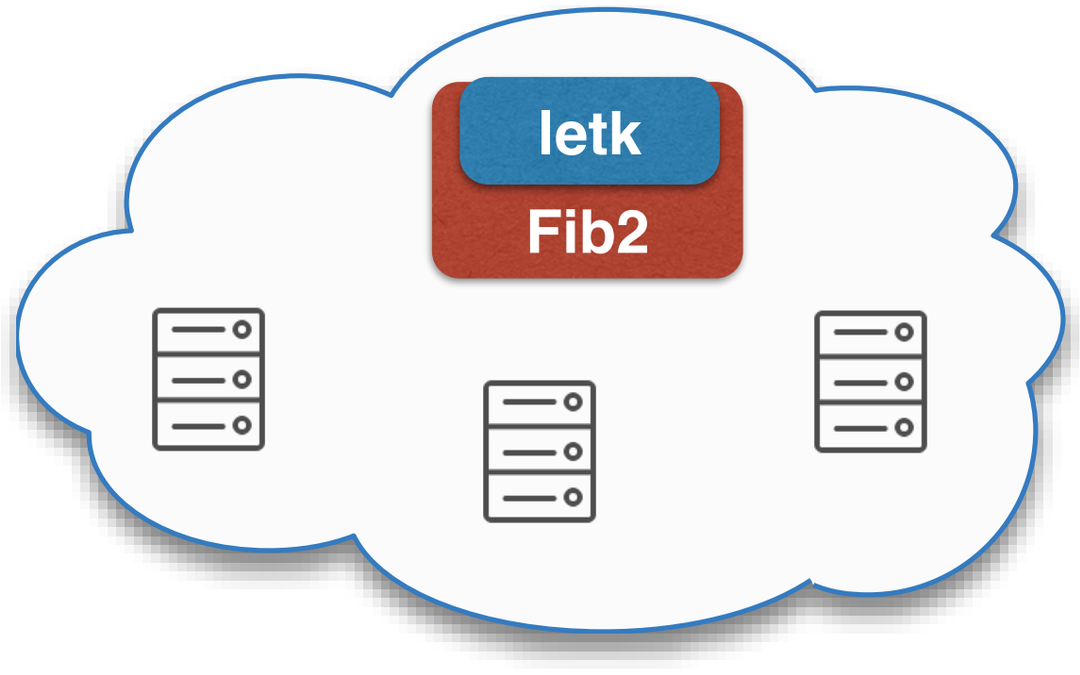
```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    if n = 0 ∨ n = 1
      k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
         in letk y = this♯fib⟨n − 2⟩
            in k⟨x + y⟩
}
```



Server Placement

Are First-Class Servers VMs?

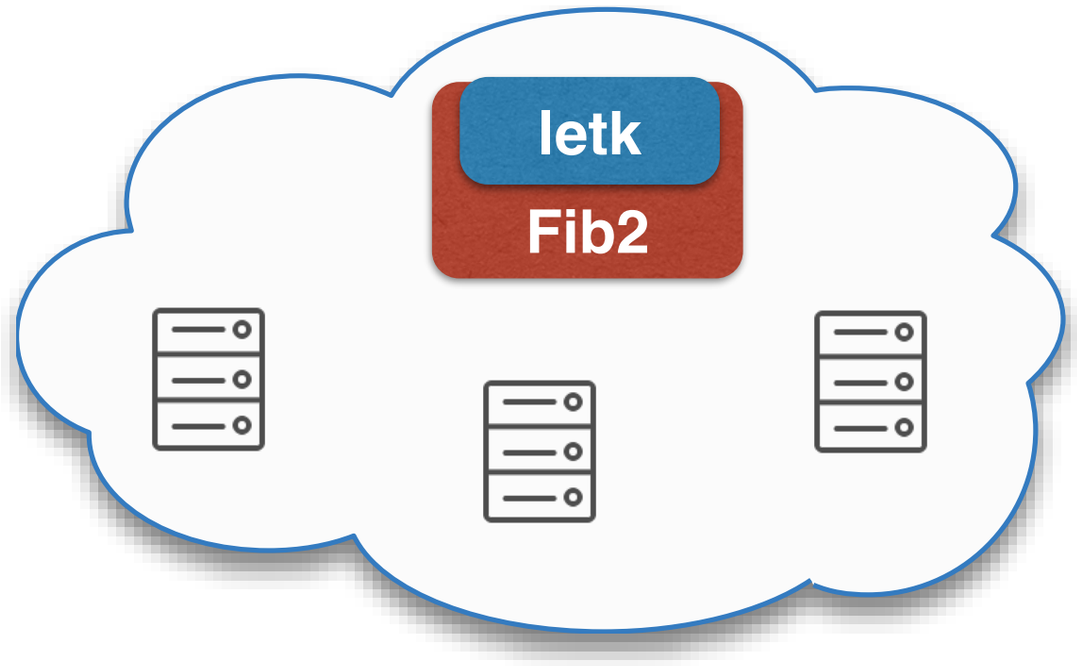
```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    if n = 0 ∨ n = 1
      k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
         in letk y = this♯fib⟨n − 2⟩
            in k⟨x + y⟩
}
```



Server Placement

Are First-Class Servers VMs?

```
Fib2 = srv {
  fib⟨n, k⟩ ▷
    if n = 0 ∨ n = 1
      k⟨n⟩
    else letk x = this♯fib⟨n − 1⟩
         in letk y = this♯fib⟨n − 2⟩
            in k⟨x + y⟩
}
```



Current implementation: Annotations for locality

Future work: Automated placement by run time

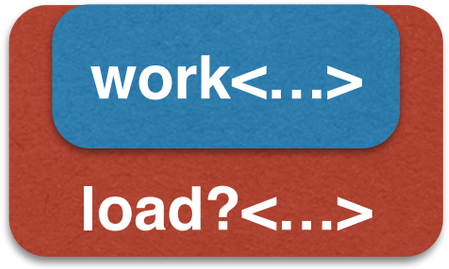
Server & Service Combinators

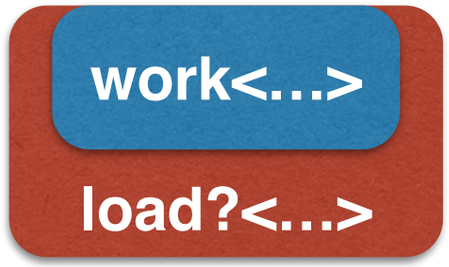
Server & Service Combinators

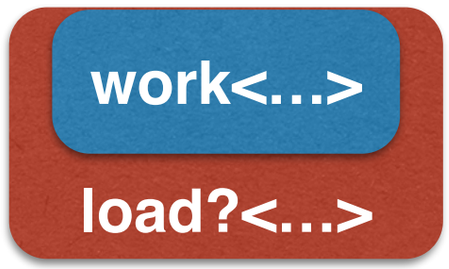
Load Balancing

Server & Service Combinators

Load Balancing

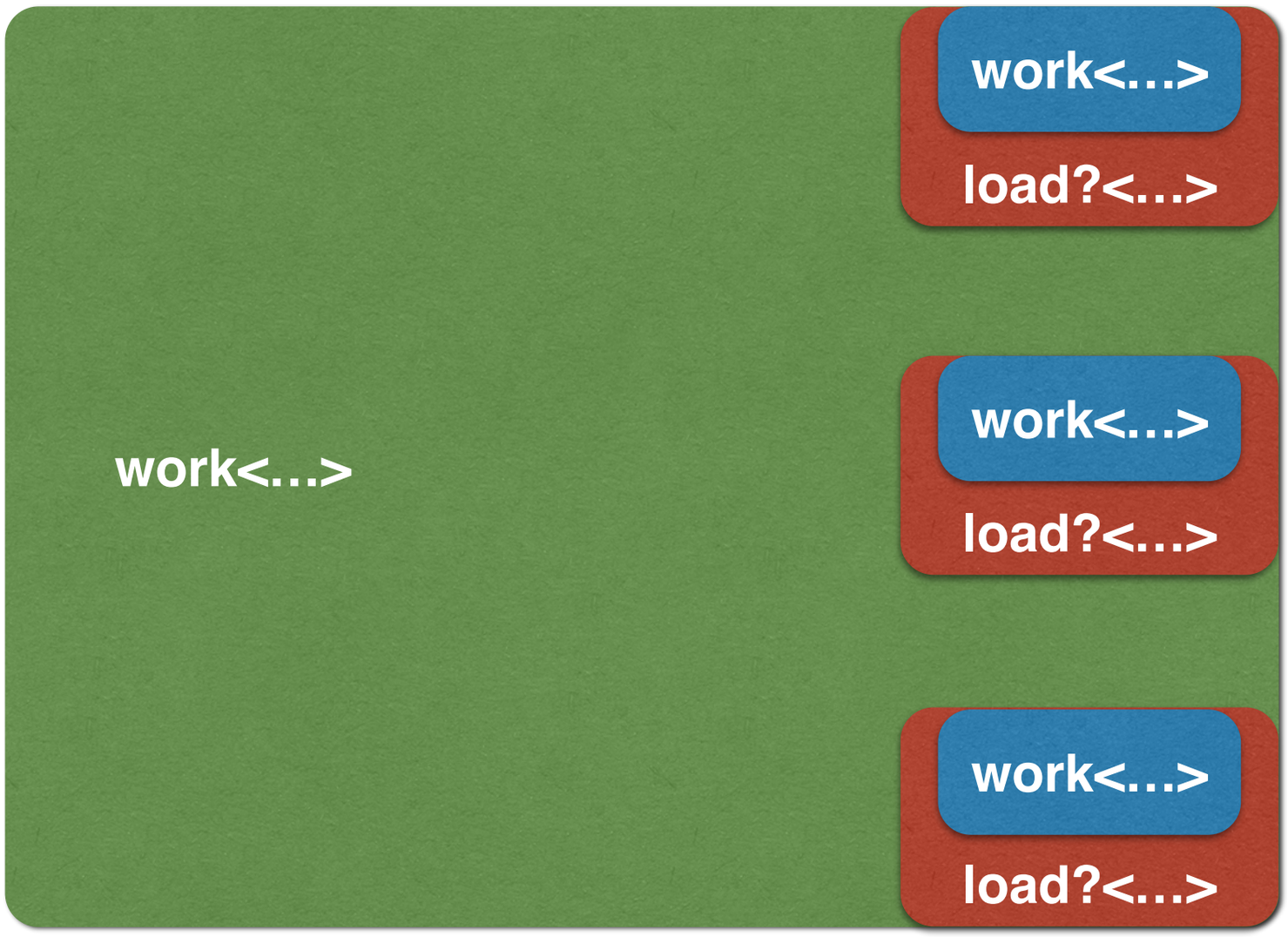






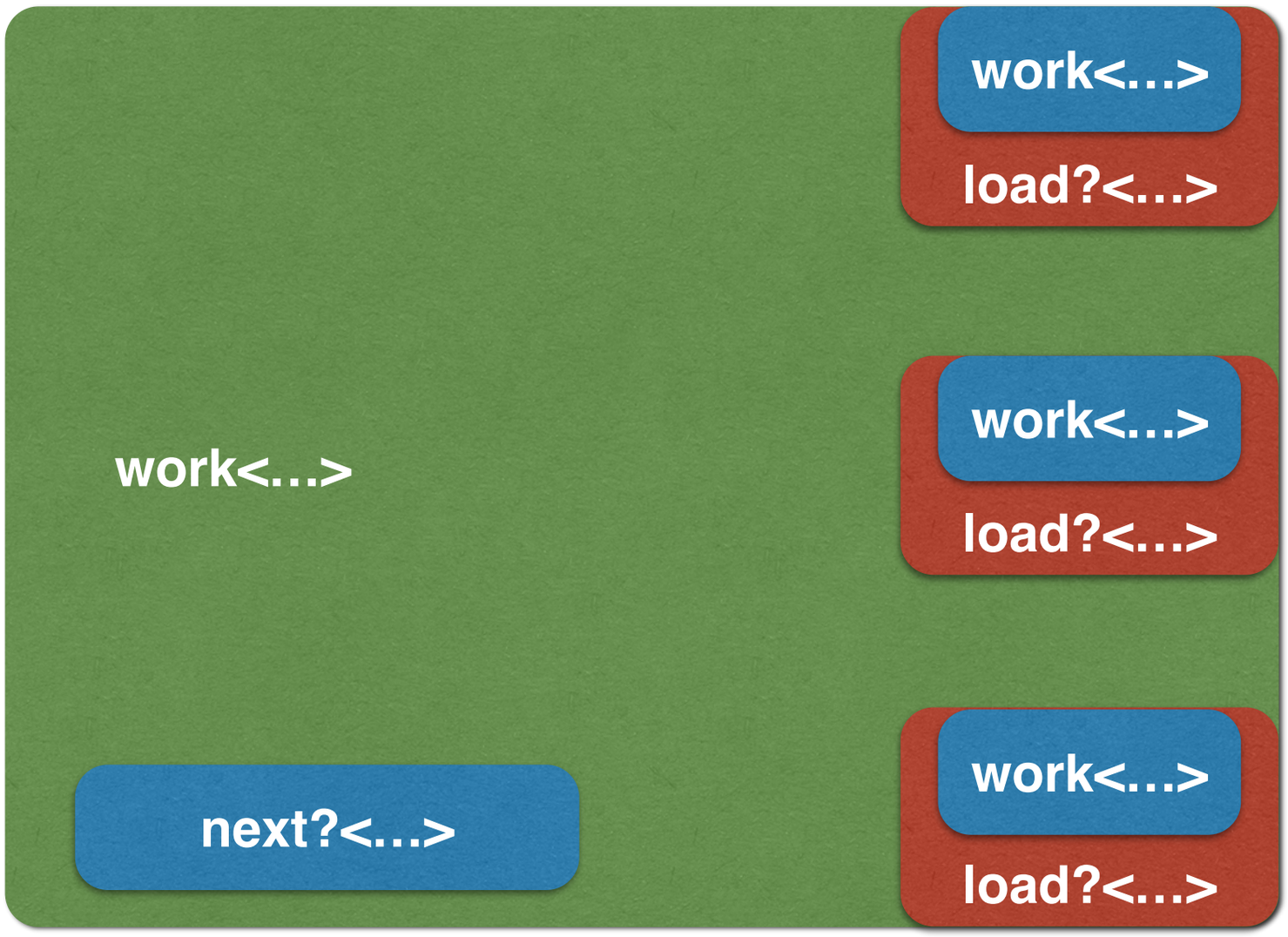
Server & Service Combinators

Load Balancing



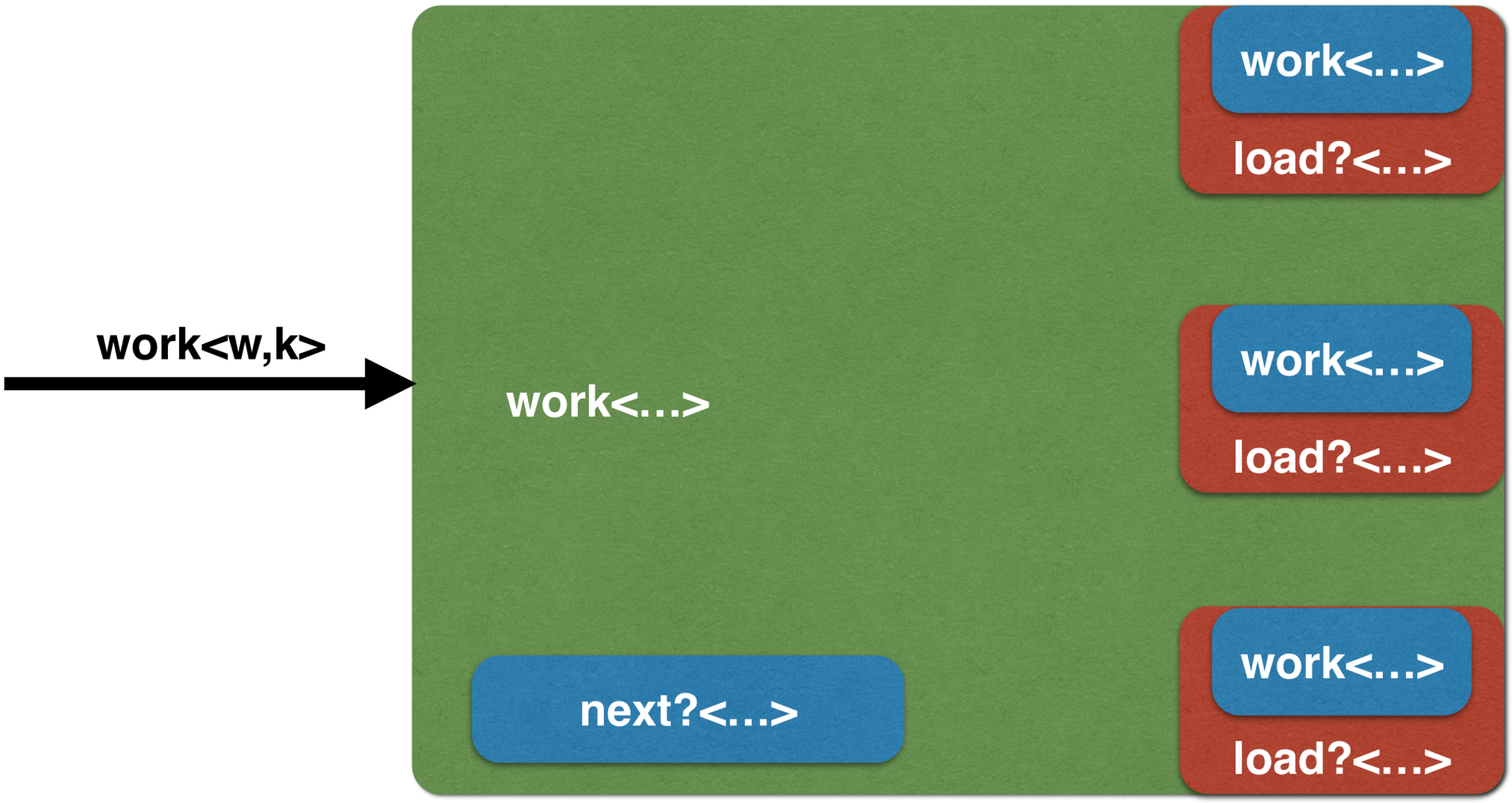
Server & Service Combinators

Load Balancing



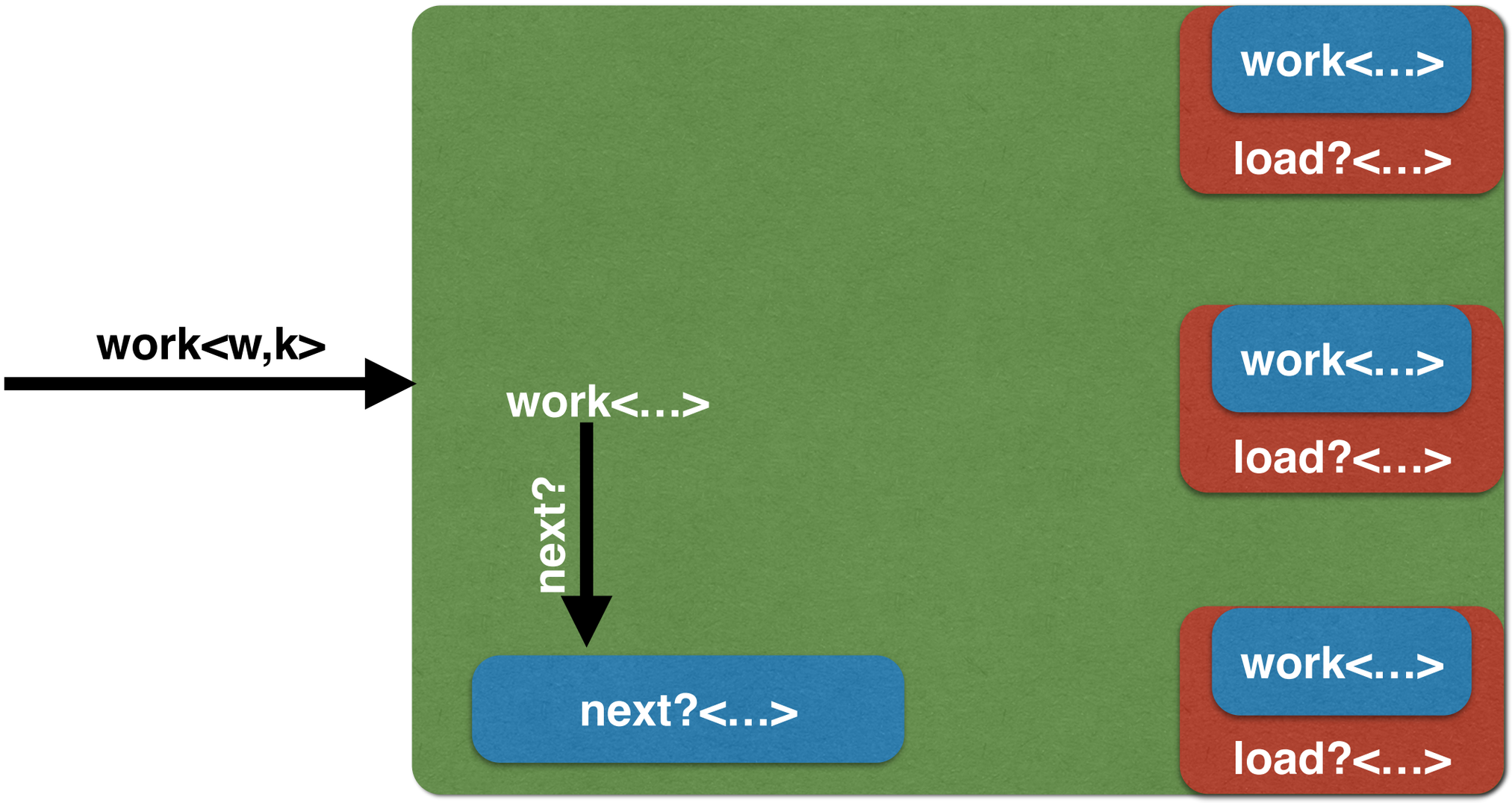
Server & Service Combinators

Load Balancing



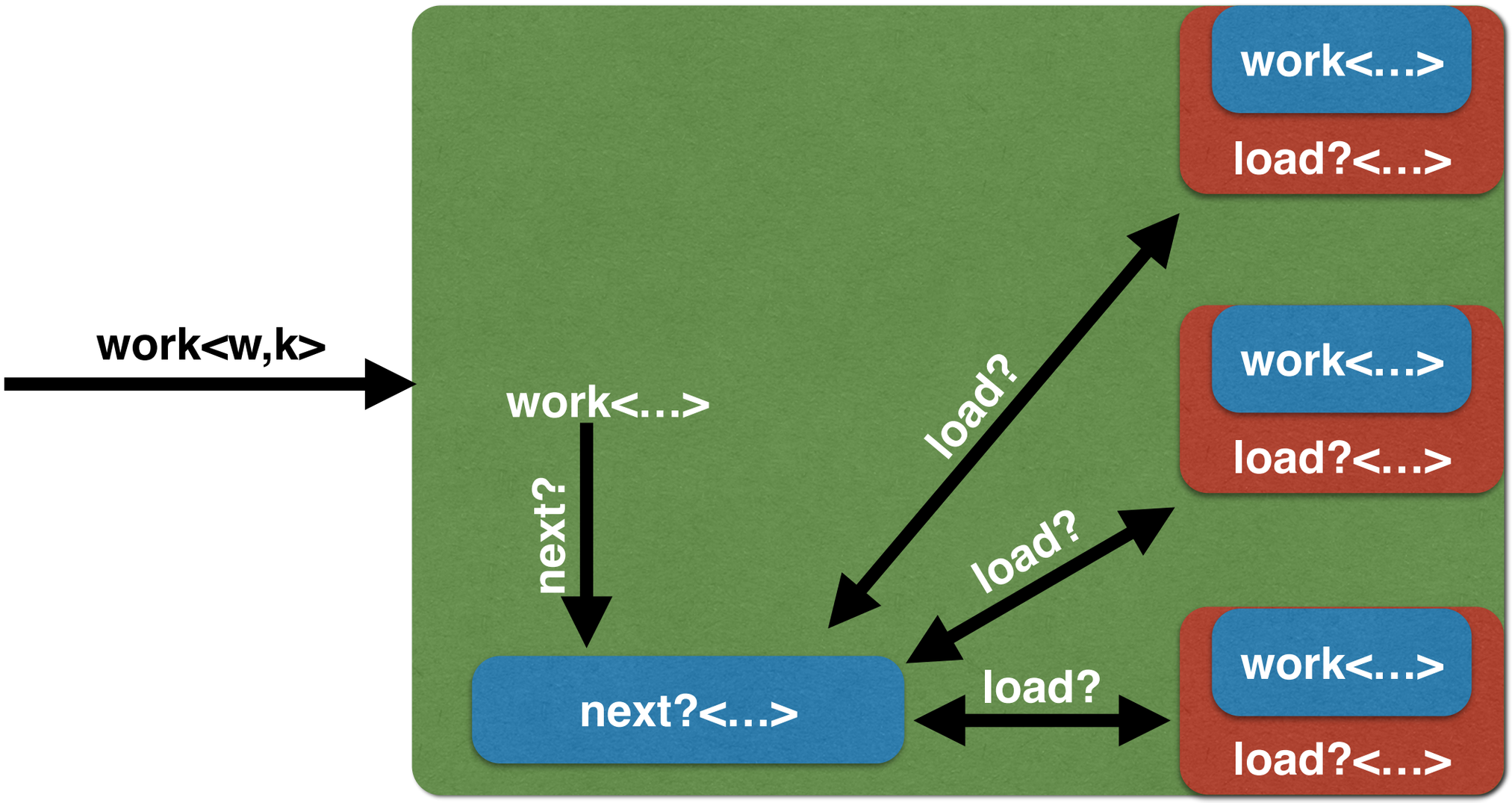
Server & Service Combinators

Load Balancing



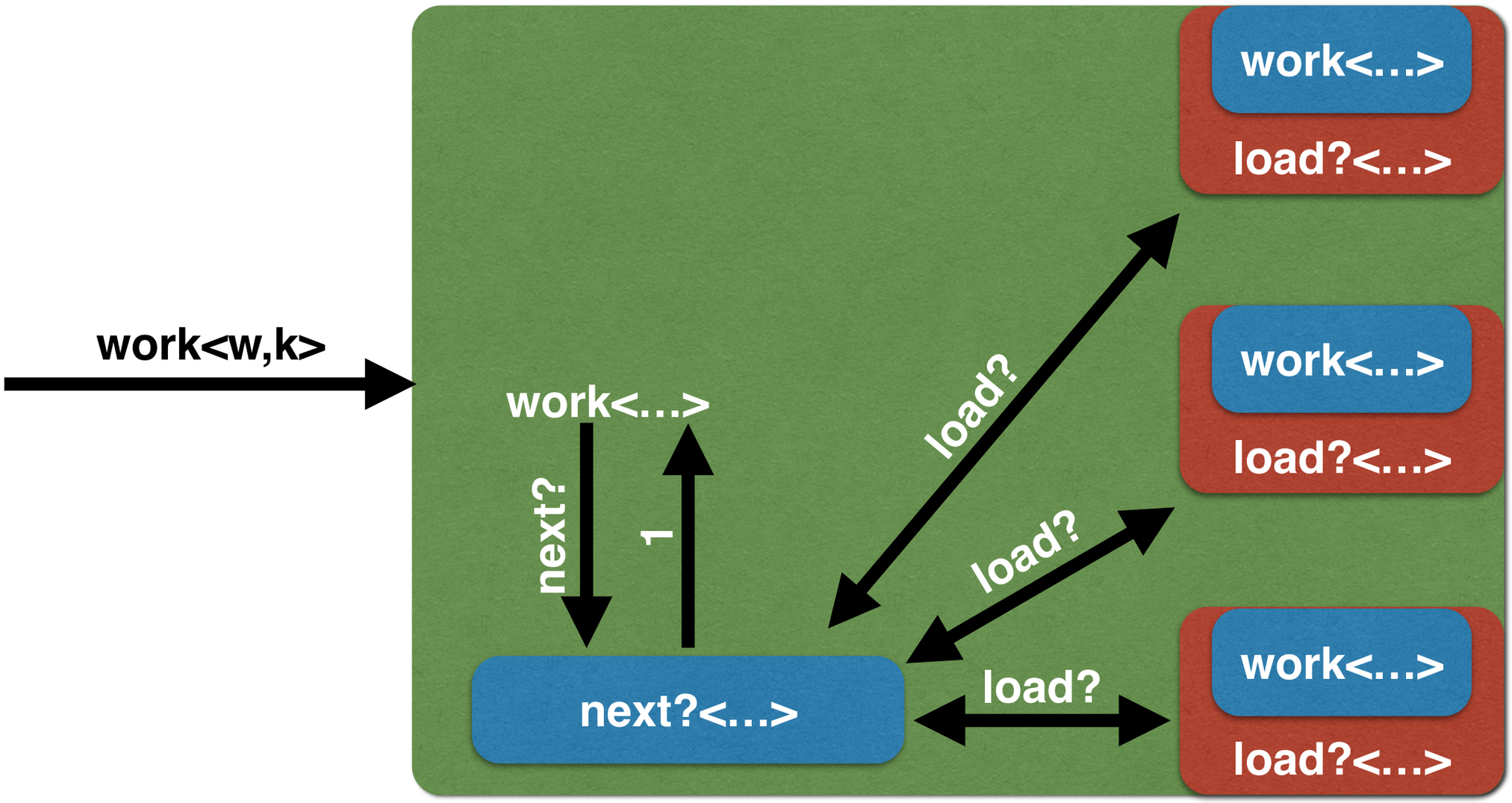
Server & Service Combinators

Load Balancing



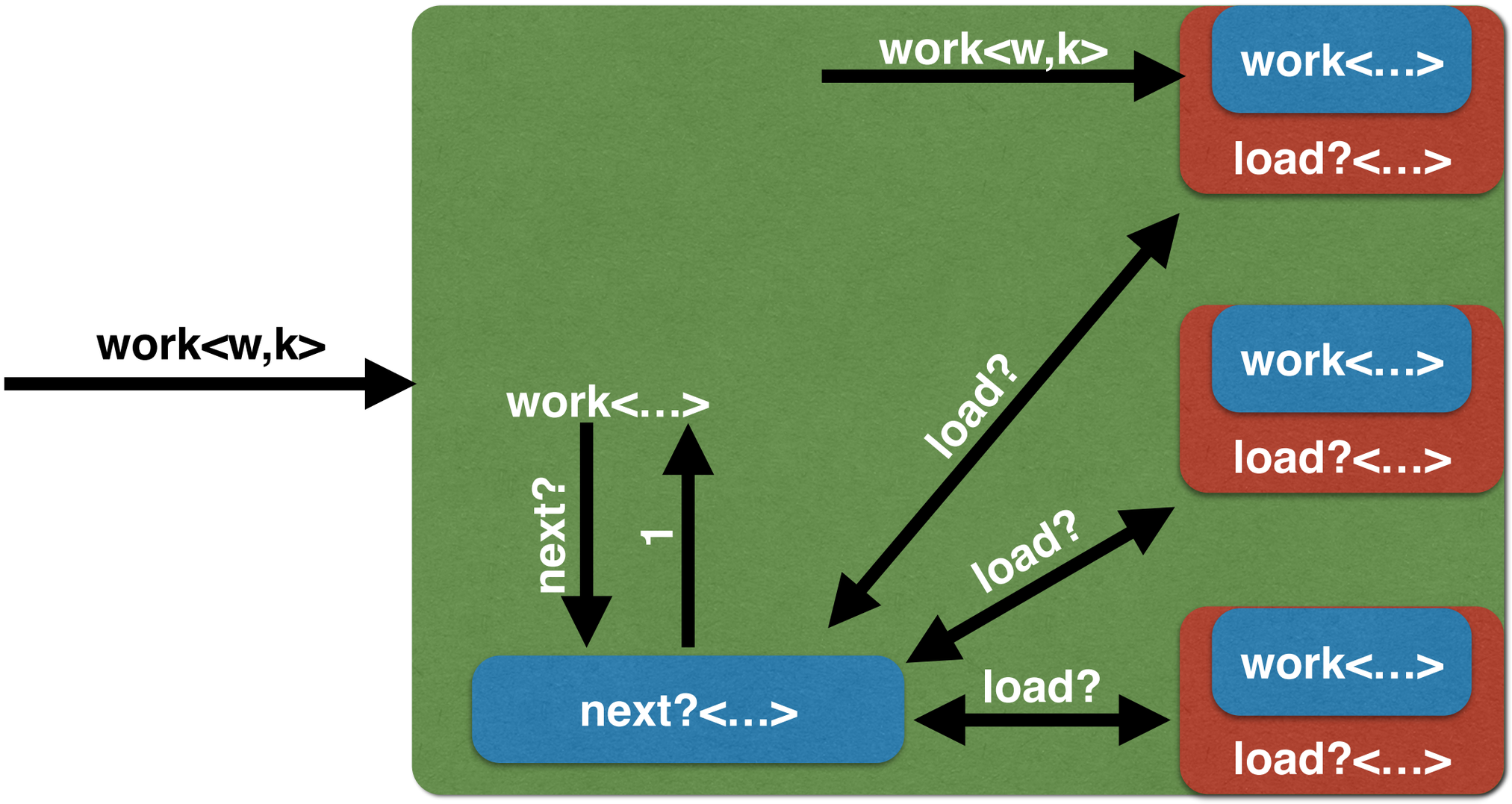
Server & Service Combinators

Load Balancing



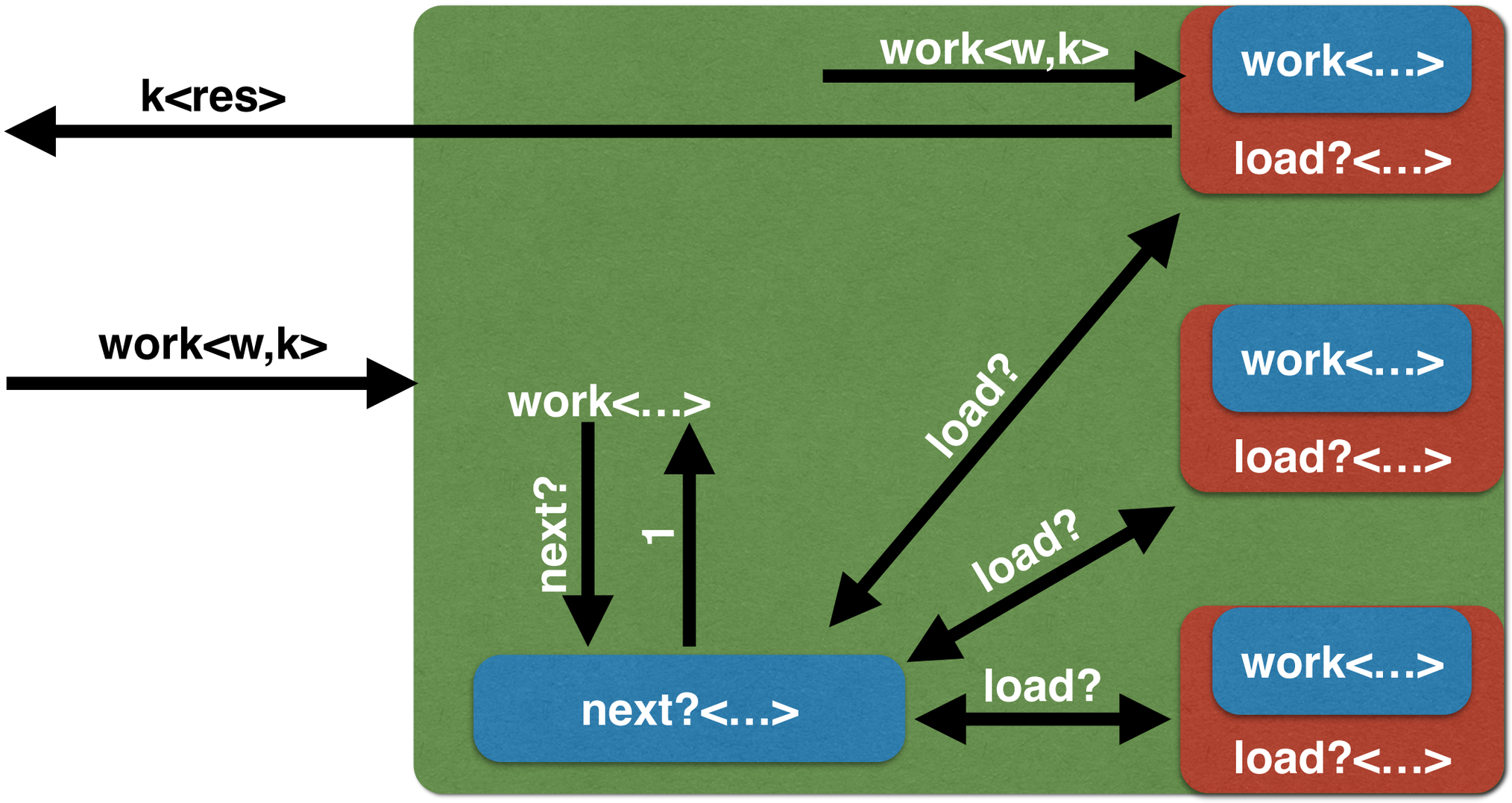
Server & Service Combinators

Load Balancing

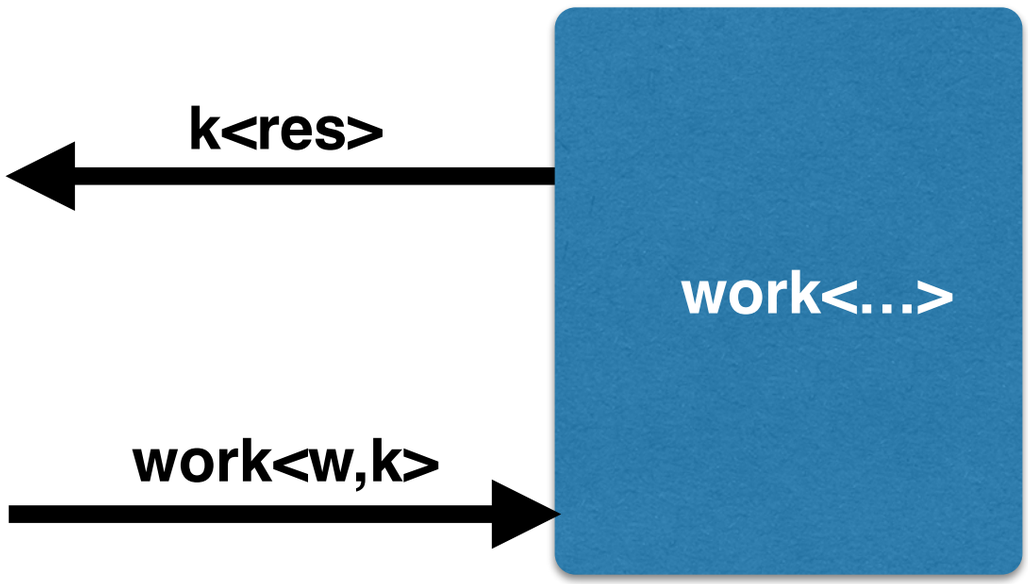


Server & Service Combinators

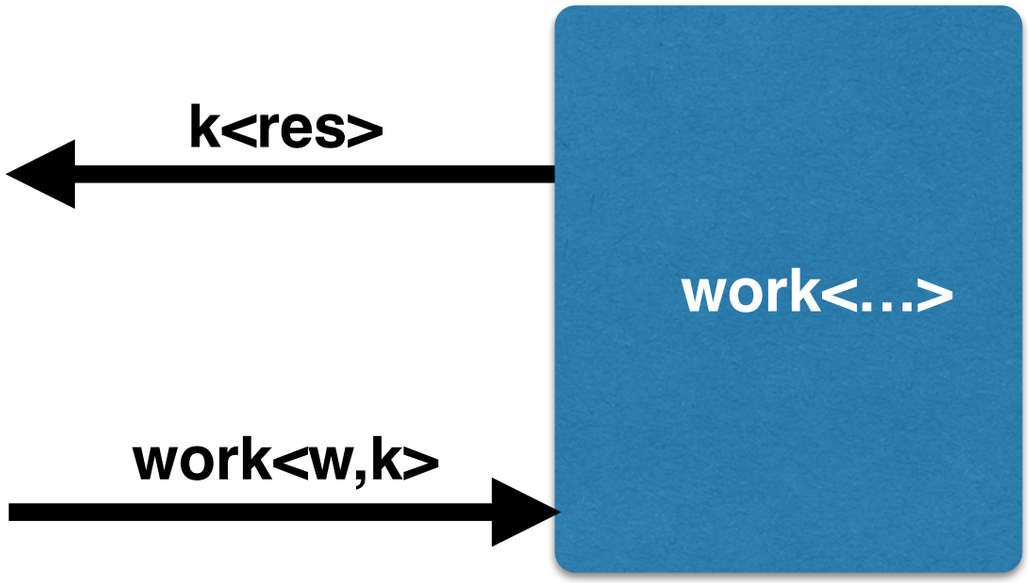
Load Balancing



Server & Service Combinators



Server & Service Combinators

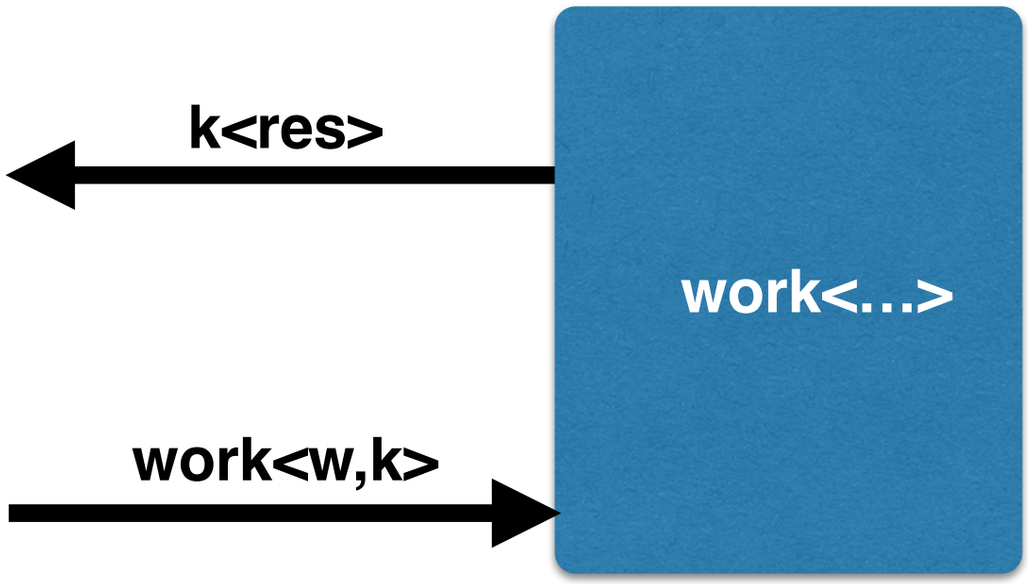


First class deployment pattern!

```
{ //...
  "Parameters" : {
    "InstanceType" : {
      "Description" : "WebServer EC2 instance type",
      "Type" : "String",
      "Default" : "t2.small",
      "AllowedValues" : [ "t2.micro", "t2.small",
      "ConstraintDescription" : "must be a valid EC2 instance type."
    } //...
  },
  "Resources" : {
    "WebServer": {
      "Type" : "AWS::EC2::Instance",
      "Properties": {
        "InstanceType"   : { "Ref" : "InstanceType" },
        "UserData" : { "Fn::Base64" : { "Fn::Join" : ["", [
                    "#!/bin/bash -xe\n",
                    "yum update -y aws-cfn-bootstrap\n",

                    "/opt/aws/bin/cfn-init -v ",
                    "      --stack ", { "Ref" : "AWS::StackName" },
                    "      --resource WebServer ",
                    "      --configsets wordpress_install ",
                    "      --region ", { "Ref" : "AWS::Region" },"\n"
        ]]}}, //...
      },
    }
  },
  "Outputs" : {
    "WebsiteURL" : {
      "Value" : { "Fn::Join" : ["", ["http://", { "Fn::GetAtt" :
[ "WebServer", "PublicDnsName" ]}, "/wordpress" ]]},
      "Description" : "WordPress Website"
    }
  }
}
```

Server & Service Combinators



First class deployment pattern!

```
{ //...
  "Parameters" : {
    "InstanceType" : {
      "Description" : "WebServer EC2 instance type",
      "Type" : "String",
      "Default" : "t2.small",
      "AllowedValues" : [ "t2.micro", "t2.small",
      "ConstraintDescription" : "must be a valid EC2 instance type."
    } //...
  },
  "Resources" : {
    "WebServer": {
      "Type" : "AWS::EC2::Instance",
      "Properties": {
        "InstanceType"   : { "Ref" : "InstanceType" },
        "UserData" : { "Fn::Base64" : { "Fn::Join" : ["", [
                    "#!/bin/bash -xe\n",
                    "yum update -y aws-cfn-bootstrap\n",

                    "/opt/aws/bin/cfn-init -v ",
                    "      --stack ", { "Ref" : "AWS::StackName" },
                    "      --resource WebServer ",
                    "      --configsets wordpress_install ",
                    "      --region ", { "Ref" : "AWS::Region" },"\n"
      ]]}}, //...
      },
    }
  },
  "Outputs" : {
    "WebsiteURL" : {
      "Value" : { "Fn::Join" : ["", ["http://", { "Fn::GetAtt" :
[ "WebServer", "PublicDnsName" ]}, "/wordpress" ]]},
      "Description" : "WordPress Website"
    }
  }
}
```

Further combinators in the paper:

MapReduce Failure Recovery

Structural Type System

Based on System $F_{<:}$

Depth- & Width-Subtyping

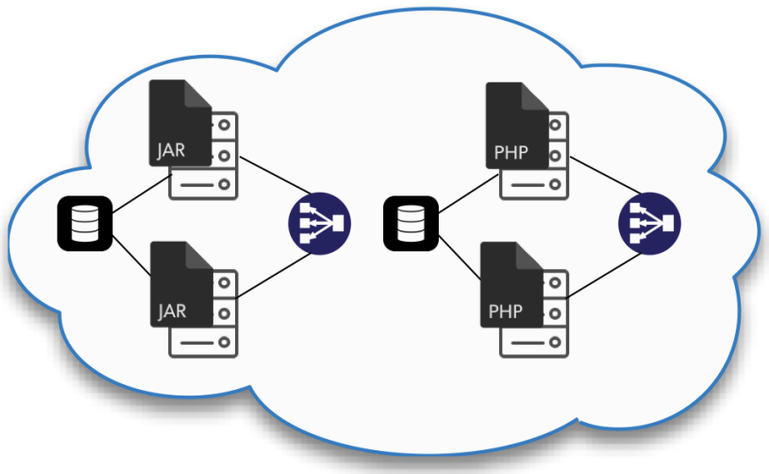
$$\texttt{Fib2} :: \mathbf{srv}\ \{\ \texttt{fib}\colon \langle \mathsf{Int}, \langle \mathsf{Int} \rangle \rangle\ \}$$
$$\texttt{Fib} :: \mathbf{srv}\ \{\ \texttt{fib}\colon \langle \mathsf{Int}, \langle \mathsf{Int} \rangle \rangle, \texttt{acc}\colon \langle \mathsf{Int}, \mathsf{Int}, \mathsf{Int}, \langle \mathsf{Int} \rangle \rangle\ \}$$

$$\texttt{Fib} <: \texttt{Fib2}$$

Bounded Polymorphism

$$\texttt{MKBalanced} :: \forall\alpha.\forall\omega <: \mathsf{TLAWorker}[\alpha].\ \mathbf{srv}\ \{\ \texttt{make}\colon (\mathsf{List}[\omega], \mathsf{Choose}[\omega]) \to \mathsf{TWorker}[\alpha]\ \}$$

Service Requests “Can’t Go Wrong”: Soundness Proof in Techreport



Summary & Outlook

Cloud Deployment DSLs

- Inextensible middleware
- Two-phase staging
- Unsafe parameterization

CPL

- Middleware combinators
- Dynamic Deployment
- First-class servers, CPS, Types

Paper

- Formal syntax & semantics
- Combinators for load balancing, fault tolerance, MapReduce
- Concurrent, single machine implementation in Scala

Ongoing Work

- Distributed, cloud-based implementation

λ Calculus Encoding

$$\lambda x.\ e \rightsquigarrow \mathbf{spwn}\ (\mathbf{srv}\ \mathtt{app}\langle x, k\rangle \triangleright \mathsf{T}(e, k)), \quad \text{where } k \text{ is fresh}$$

$$\mathsf{T}(\lambda x.\ e, k) = k\langle \mathbf{spwn}\ (\mathbf{srv}\ \mathtt{app}\langle x, k\rangle \triangleright \mathsf{T}(e, k))\rangle$$

$$\begin{aligned}
\mathsf{T}((f\ e), k) = \mathsf{T}(f, (\mathbf{spwn}\ (\mathbf{srv}\ \mathtt{k_1}\langle v_f\rangle \triangleright \quad & \text{where } v_f \text{ is fresh} \\
\mathsf{T}(e, (\mathbf{spwn}\ (\mathbf{srv}\ \mathtt{k_2}\langle v_e\rangle \triangleright \quad & \text{where } v_e \text{ is fresh} \\
v_f \sharp \mathtt{app}\langle v_e, k\rangle))\sharp \mathtt{k_2})))\sharp \mathtt{k_1}) &
\end{aligned}$$

$$\mathsf{T}(e, k) \quad = k\langle e\rangle$$

[Fournet and Gonthier '96]

Derived Syntax

$$\textbf{let}\ x = e_1\ \textbf{in}\ e_2 \quad \rightsquigarrow \quad (\textbf{spwn}\ (\textbf{srv}\ \texttt{let}\langle x\rangle \triangleright e_2))\sharp\texttt{let}\langle e_1\rangle$$

$$\textbf{letk}\ x = e_1\langle \overline{e}\rangle\ \textbf{in}\ e_2 \rightsquigarrow e_1\langle \overline{e}, (\textbf{spwn}\ (\textbf{srv}\ \texttt{k}\langle x\rangle \triangleright e_2))\sharp\texttt{k}\rangle$$

$$\textbf{thunk}\ \ e \rightsquigarrow \textbf{srv}\ \texttt{force}\langle k\rangle \triangleright k\langle e\rangle$$