Modular I/O Reasoning in DimSum

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Modular I/O Reasoning

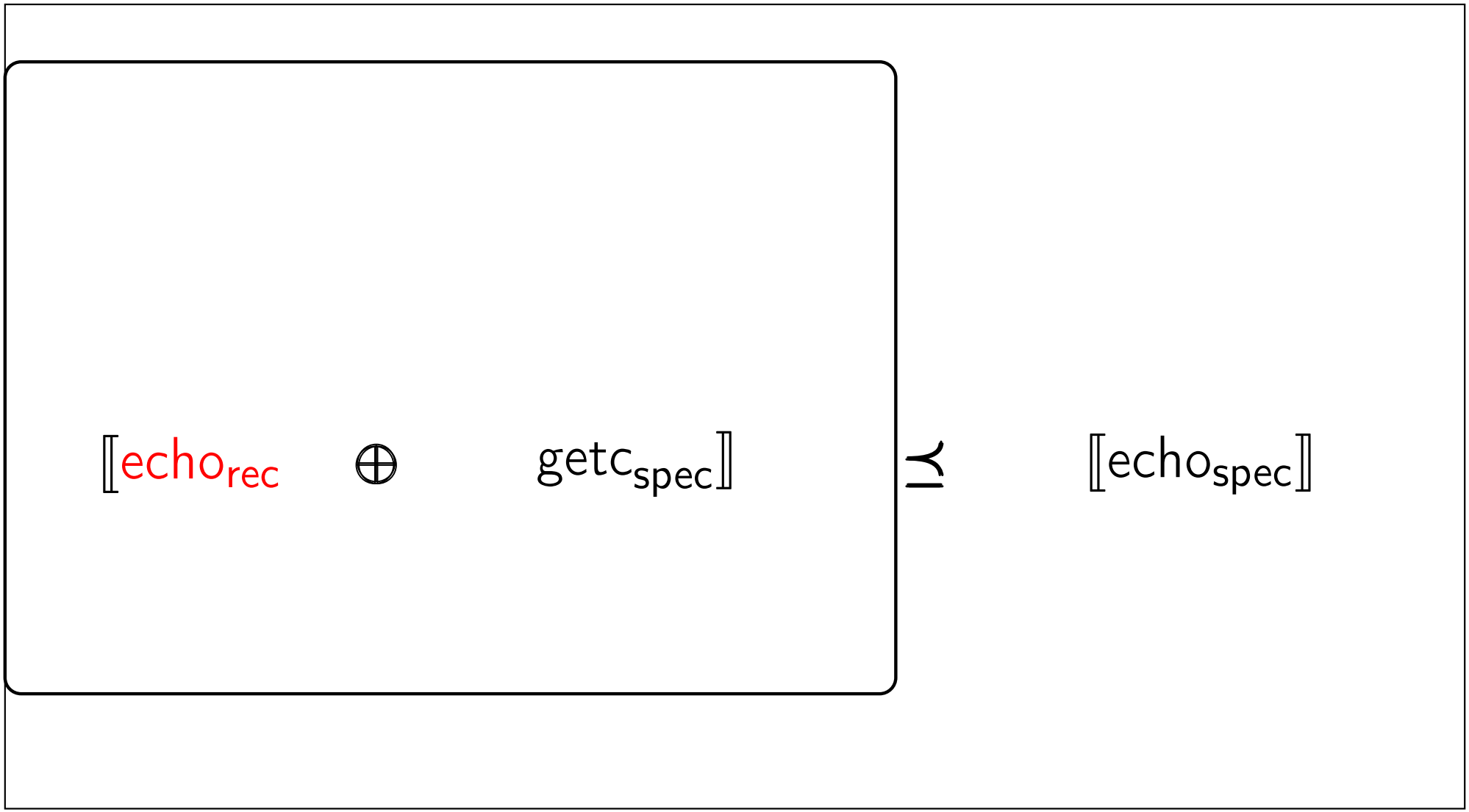
Multi-language Reasoning in DimSum

Rotation Project

Summary

- Formally verified compiler
  - Proof covers all optimizations
  - Correct w.r.t. the modeled semantics
- Discrepancies between hardware and model
  - Cannot implement correct calling conventions
  - Cannot support TriCore architecture
- Suboptimal code generation
  - Inserted moves
  - Higher register pressure

Example


$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!]$
$\preceq$
$[\![\mathsf{echo}_{\mathsf{spec}}]\!]$

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int echo () :=
  let c := getc();
  putc(c);
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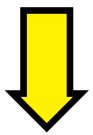
Example

(Call f vs h)



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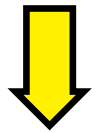

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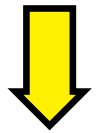

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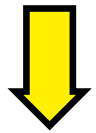

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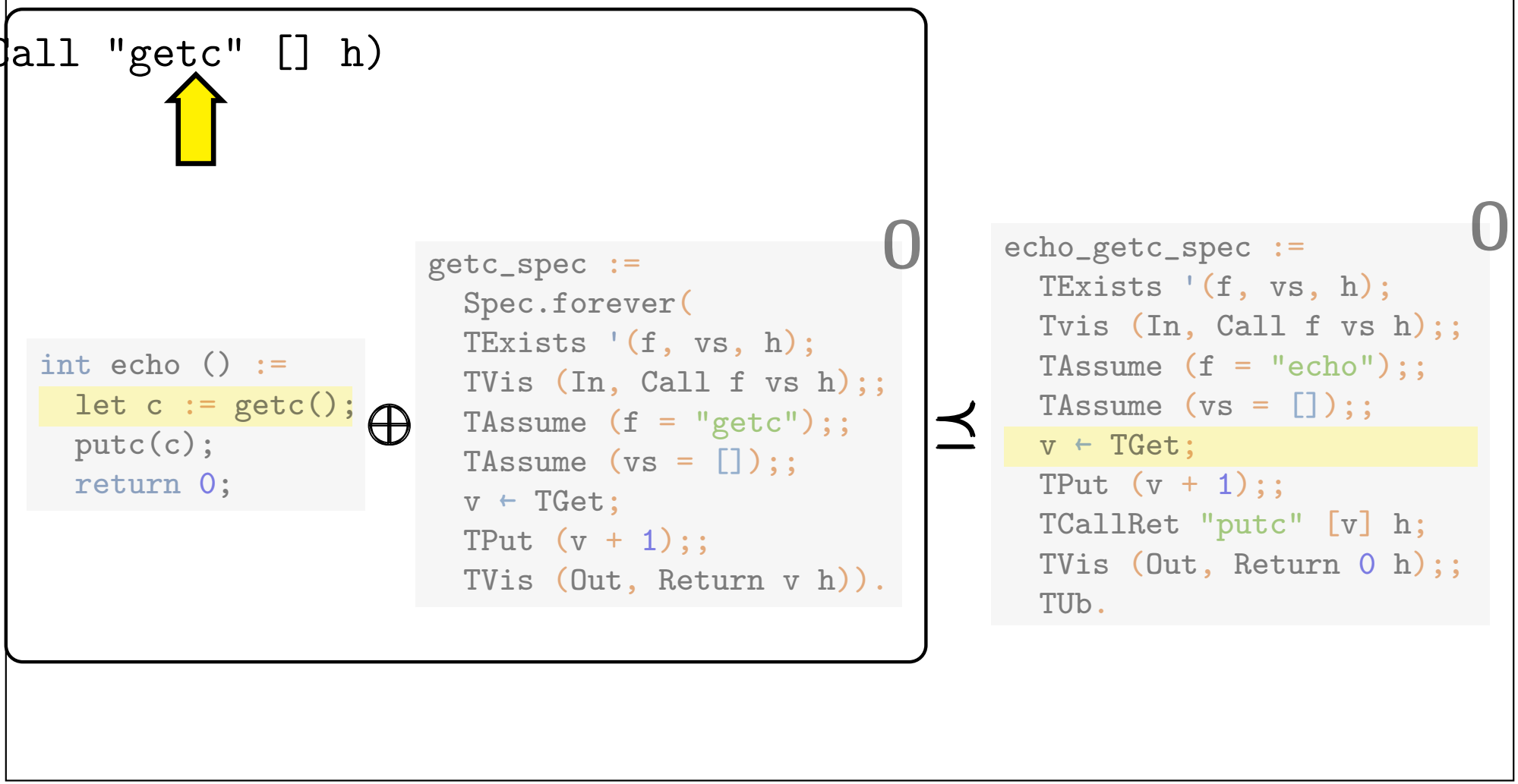
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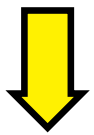

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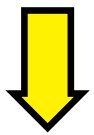

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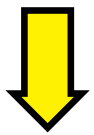

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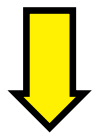

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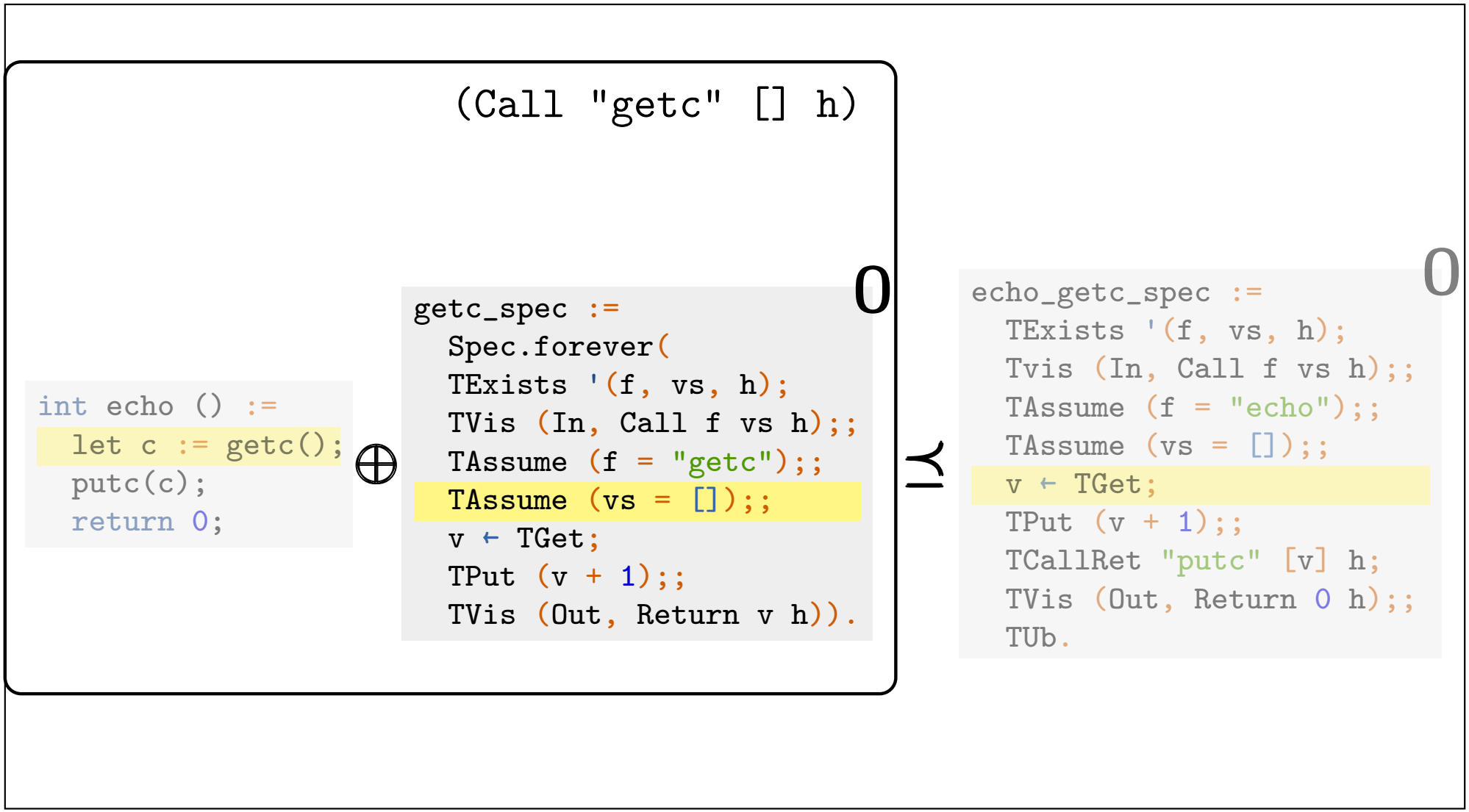
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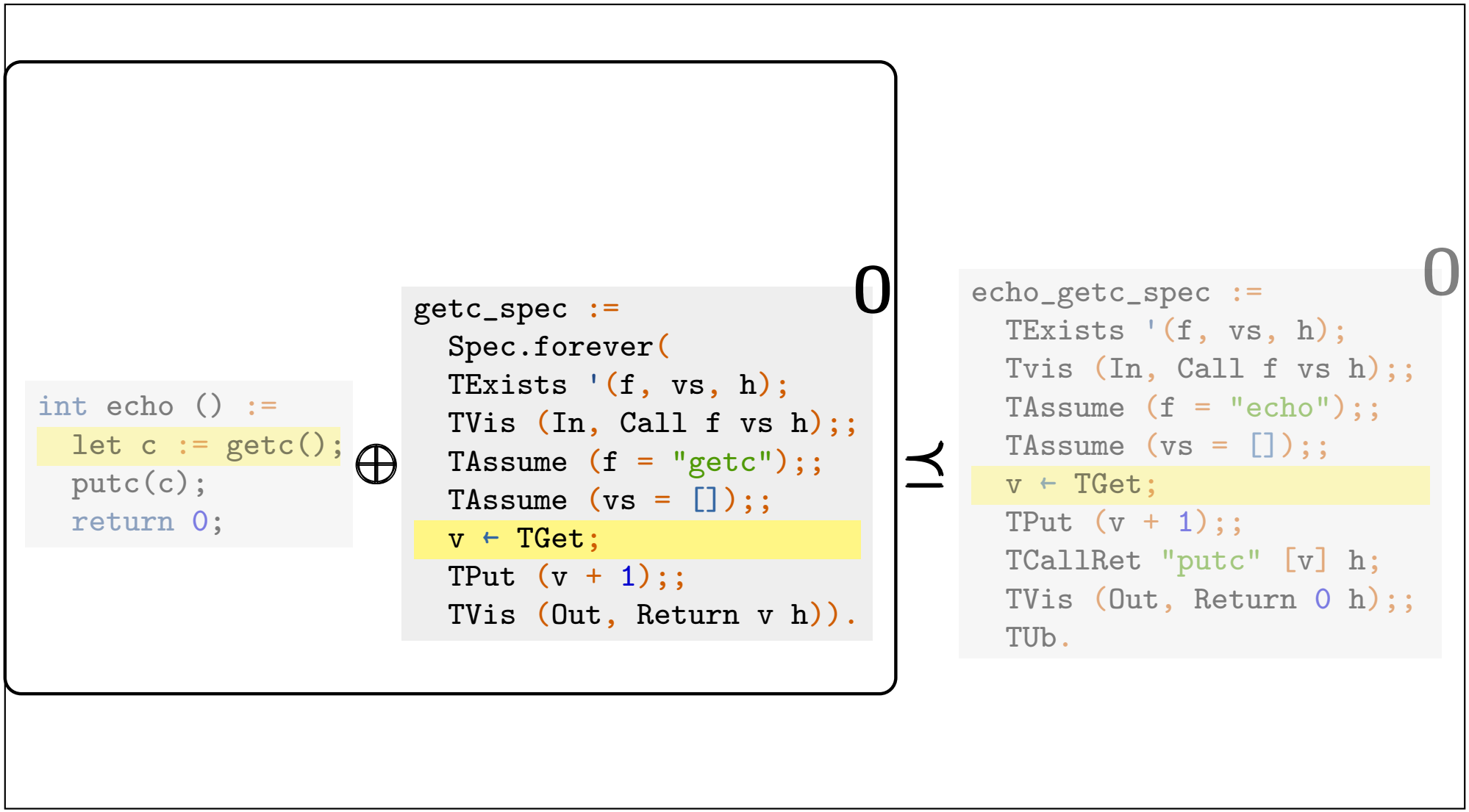
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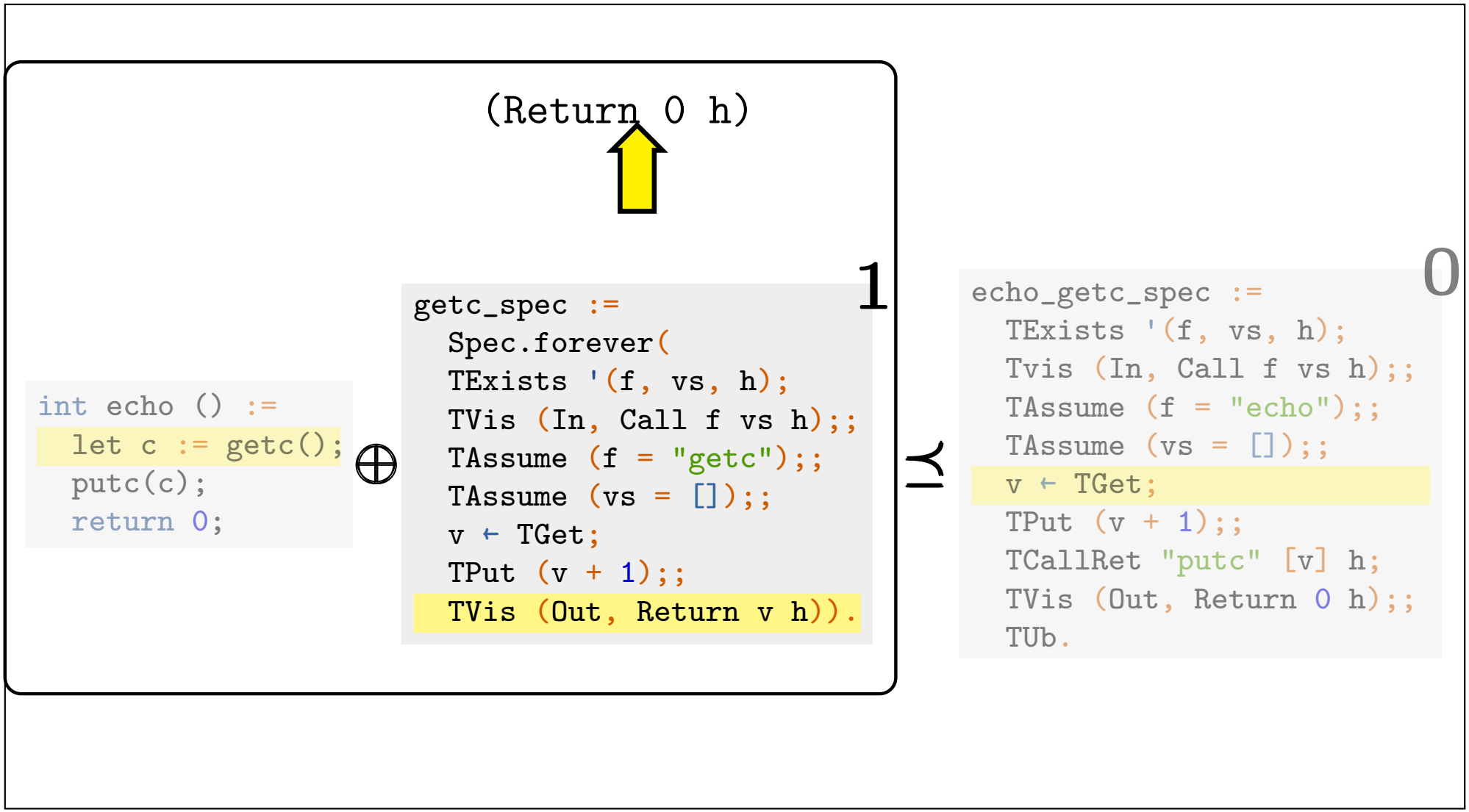
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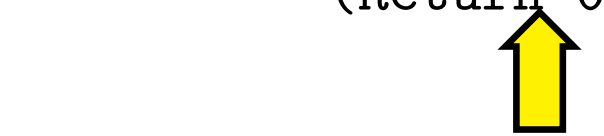
Example

(Return 0 h)



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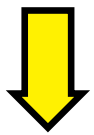
(Return 0 h)



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Example

Call "putc" 0 h)

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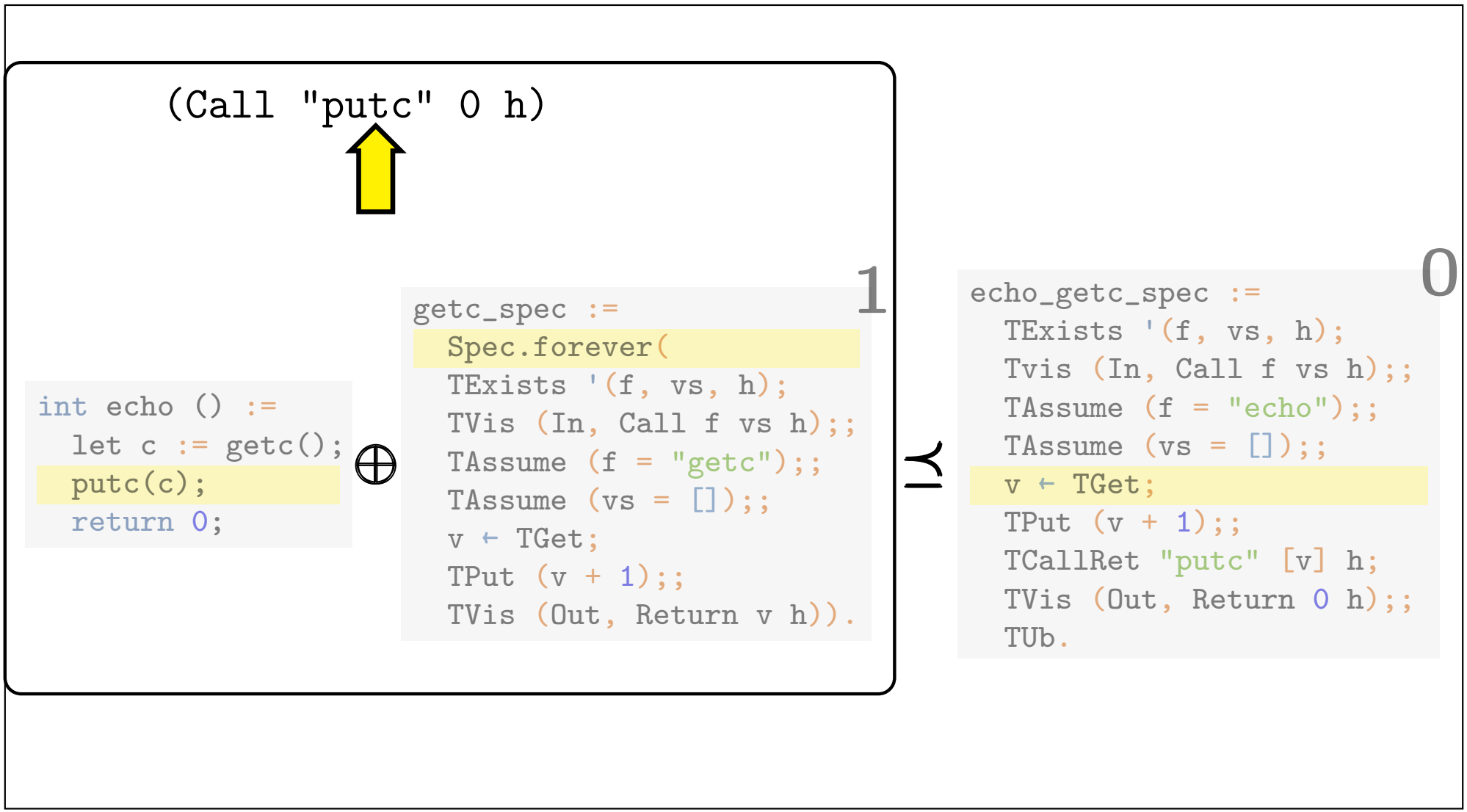
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

Example


(Call "putc" 0 h)
int echo () :=
let c := getc();
putc(c);
return 0;
getc_spec :=
Spec.forever(
TExists '(f, vs, h);
TVis (In, Call f vs h);;
TAssume (f = "getc");;
TAssume (vs = []);;
v ← TGet;
TPut (v + 1);;
TVis (Out, Return v h)).
1
echo_getc_spec :=
TExists '(f, vs, h);
Tvis (In, Call f vs h);;
TAssume (f = "echo");;
TAssume (vs = []);;
v ← TGet;
TPut (v + 1);;
TCallRet "putc" [v] h;
TVis (Out, Return 0 h);;
TUb.
0

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

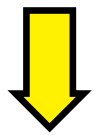
⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

≻1

(Call "putc" 0 h)



```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

0

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

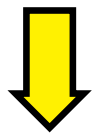
⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

≻1

(Call "putc" 0 h)



```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

0

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

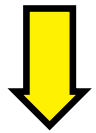
⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

≺1

(Call "putc" 0 h)



```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

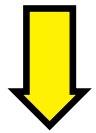
⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

≺1

(Call "putc" 0 h)



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  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
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  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

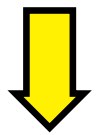
$\oplus$

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

$\rightarrow$

(Call "putc" 0 h)



```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

$\oplus$

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

$\preceq_{\Upsilon}$

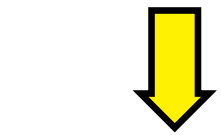
(Return v h)

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

(Return v h)



```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

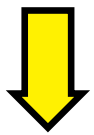
≤

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

(Return v h)



```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

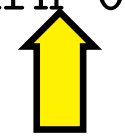
≺

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

(Return 0 h)



```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

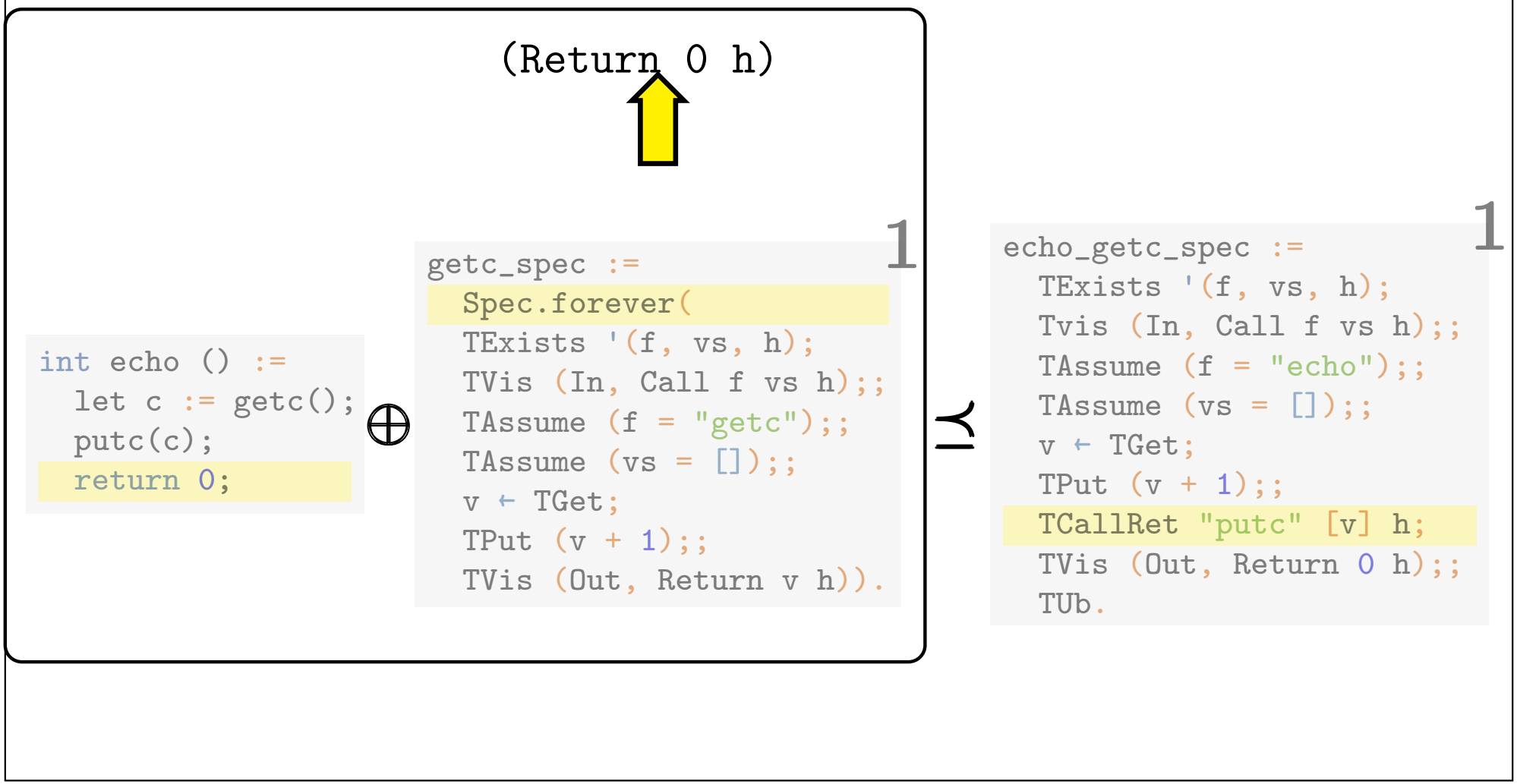
1

≤

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example


(Return 0 h)
int echo () :=
let c := getc();
putc(c);
return 0;
getc_spec :=
Spec.forever(
TExists '(f, vs, h);
TVis (In, Call f vs h);;
TAssume (f = "getc");;
TAssume (vs = []);;
v ← TGet;
TPut (v + 1);;
TVis (Out, Return v h)).
1
echo_getc_spec :=
TExists '(f, vs, h);
Tvis (In, Call f vs h);;
TAssume (f = "echo");;
TAssume (vs = []);;
v ← TGet;
TPut (v + 1);;
TCallRet "putc" [v] h;
TVis (Out, Return 0 h);;
TUb.
1

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

⊕

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

⪯

(Return 0 h)

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Example

```
int echo () :=
  let c := getc();
  putc(c);
  return 0;
```

$\oplus$

```
getc_spec :=
  Spec.forever(
  TExists '(f, vs, h);
  TVis (In, Call f vs h);;
  TAssume (f = "getc");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TVis (Out, Return v h)).
```

1

$\succ$

```
echo_getc_spec :=
  TExists '(f, vs, h);
  Tvis (In, Call f vs h);;
  TAssume (f = "echo");;
  TAssume (vs = []);;
  v ← TGet;
  TPut (v + 1);;
  TCallRet "putc" [v] h;
  TVis (Out, Return 0 h);;
  TUb.
```

1

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \quad \preceq \quad [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

Towards Hoare-style Reasoning

$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\boldsymbol{\lambda} \kappa_t \sigma_t,$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\boldsymbol{\lambda} \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\boldsymbol{\lambda} \kappa_s \sigma_s,$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\boldsymbol{\lambda} \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\boldsymbol{\lambda} \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \prod_s$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \Pi_s$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi_{\oplus}(\Pi_s)$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \Pi_s$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> (\lambda \kappa_l \sigma_l, \texttt{if \_ then } [\![\mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \ldots \texttt{ else } \Pi_s \kappa_l \sigma)$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi_{\oplus}(\Pi_s)$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \Pi_s$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> (\lambda \kappa_l \sigma_l, \texttt{if \_ then } [\![\mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \ldots \texttt{ else } \Pi_s \kappa_l \sigma)$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi_{\oplus}(\Pi_s)$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi$$

Towards Hoare-style Reasoning

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_t \sigma_t, [\![\mathsf{echo}_{\mathsf{spec}}]\!] \approx\!> (\lambda \kappa_s \sigma_s, \kappa_t = \kappa_s * \sigma_t \preceq \sigma_s))$$

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \Pi_s$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> (\lambda \kappa_l \sigma_l, \texttt{if \_ then } [\![\mathsf{getc}_{\mathsf{spec}}]\!] \approx\!> \ldots \texttt{ else } \Pi_s \kappa_l \sigma)$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi_{\oplus}(\Pi_s)$$

$$[\![\mathsf{echo}_{\mathsf{rec}}]\!] \approx\!> \Pi$$

TGT Call "echo" es @ Π {{Φ}}

(Modular) Hoare-style Reasoning

```
TGT Call "echo" es @ Π
  PRE |-*: es POST_e, ⌜es = []⌝ *
    TGT Call "getc" es @ Π
      PRE |-*: es POST, ⌜es = []⌝ *
      POST |*: ret,
        TGT Call "putc" es @ Π
          PRE |-*: es POST, ⌜es = [v]⌝ *
          POST |*: _,
  POST_e |*: ret, ⌜ret = 0⌝.
```

(Modular) Hoare-style Reasoning

```
TGT Call "getc" es @ Π
  PRE |-*: es POST, ∃ v, P v * ⌜es = []⌝ *
  POST |*: ret, ⌜ret = v⌝ * P (v + 1).
```

```
TGT Call "echo" es @ Π
  PRE |-*: es POST_e, ⌜es = []⌝ *
    TGT Call "getc" es @ Π
      PRE |-*: es POST, ⌜es = []⌝ *
      POST |*: ret,
        TGT Call "putc" es @ Π
          PRE |-*: es POST, ⌜es = [v]⌝ *
          POST |*: _,
  POST_e |*: ret, ⌜ret = 0⌝.
```

(Modular) Hoare-style Reasoning

```
TGT Call "getc" es @ Π
  PRE |-*: es POST, ∃ v, P v * ⌜es = []⌝ *
  POST |*: ret, ⌜ret = v⌝ * P (v + 1).
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```
TGT Call "echo" es @ Π
  PRE |-*: es POST_e, ∃ v, P v * ⌜es = []⌝ *
    TGT Call "putc" es @ Π
      PRE |-*: es POST, P (v + 1) * ⌜es = [v]⌝ *
      POST |*: _, P (v + 1) (*)
  POST_e |*: ret, ⌜ret = 0⌝ * P (v + 1).
```

Example 1

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

```
Lemma sim_getc_spec `{!specGS} Π Φ :
  switch Π
    PRE |-*: κ σ1 POST,
      ∃ f es h, ⌜κ = Some (Incoming, ERCall f es h)⌝ ∗
    POST Tgt _ _ |*: σ' Π',
      ∃ v, ⌜f = "getc"⌝ ∗ ⌜es = []⌝ ∗ spec_state v ∗ ⌜σ' = σ1⌝ (*)
  switch Π'
    PRE |-*: κ σ POST,
      ⌜κ = Some (Outgoing, ERReturn (ValNum v) h)⌝ ∗ spec_state (v + 1) ∗
    POST Tgt _ _ |*: σ' Π'',
      ⌜σ' = σ⌝ ∗ ⌜Π'' = Π⌝ ∗ TGT getc_spec @ Π {{ Φ }} -*
  TGT getc_spec @ Π {{ Φ }}.
```

Example 1

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

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    PRE |-*: κ σ1 POST,
      ∃ f es h, ⌜κ = Some (Incoming, ERCall f es h)⌝ ∗
    POST Tgt _ _ |*: σ' Π',
      ∃ v, ⌜f = "getc"⌝ ∗ ⌜es = []⌝ ∗ spec_state v ∗ ⌜σ' = σ1⌝ (*)
  switch Π'
    PRE |-*: κ σ POST,
      ⌜κ = Some (Outgoing, ERReturn (ValNum v) h)⌝ ∗ spec_state (v + 1) ∗
    POST Tgt _ _ |*: σ' Π'',
      ⌜σ' = σ⌝ ∗ ⌜Π'' = Π⌝ ∗ TGT getc_spec @ Π {{ Φ }} -∗
  TGT getc_spec @ Π {{ Φ }}.
```

Example 1

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

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Lemma sim_getc_spec `{!specGS} Π Φ :
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    PRE |-*: κ σ1 POST,
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    POST Tgt _ _ |*: σ' Π',
      ∃ v, ⌜f = "getc"⌝ ∗ ⌜es = []⌝ ∗ spec_state v ∗ ⌜σ' = σ1⌝ (*)
  switch Π'
    PRE |-*: κ σ POST,
      ⌜κ = Some (Outgoing, ERReturn (ValNum v) h)⌝ ∗ spec_state (v + 1) ∗
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      ⌜σ' = σ⌝ ∗ ⌜Π'' = Π⌝ ∗ TGT getc_spec @ Π {{ Φ }} -∗
  TGT getc_spec @ Π {{ Φ }}.
```

Example 1

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

```
Lemma sim_getc_spec `{!specGS} Π Φ :
  switch Π
    PRE |-*: κ σ1 POST,
      ∃ f es h, ⌜κ = Some (Incoming, ERCall f es h)⌝ ∗
    POST Tgt _ _ |*: σ' Π',
      ∃ v, ⌜f = "getc"⌝ ∗ ⌜es = []⌝ ∗ spec_state v ∗ ⌜σ' = σ1⌝ (∗)
  switch Π'
    PRE |-*: κ σ POST,
      ⌜κ = Some (Outgoing, ERReturn (ValNum v) h)⌝ ∗ spec_state (v + 1) ∗
    POST Tgt _ _ |*: σ' Π'',
      ⌜σ' = σ⌝ ∗ ⌜Π'' = Π⌝ ∗ TGT getc_spec @ Π {{ Φ }} -∗
  TGT getc_spec @ Π {{ Φ }}.
```

Example 1

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

```
Lemma sim_getc_spec `{!specGS} Π Φ :
  switch Π
    PRE |-*: κ σ1 POST,
      ∃ f es h, ⌜κ = Some (Incoming, ERCall f es h)⌝ ∗
    POST Tgt _ _ |*: σ' Π',
      ∃ v, ⌜f = "getc"⌝ ∗ ⌜es = []⌝ ∗ spec_state v ∗ ⌜σ' = σ1⌝ (*)
  switch Π'
    PRE |-*: κ σ POST,
      ⌜κ = Some (Outgoing, ERReturn (ValNum v) h)⌝ ∗ spec_state (v + 1) ∗
    POST Tgt _ _ |*: σ' Π'',
      ⌜σ' = σ⌝ ∗ ⌜Π'' = Π⌝ ∗ TGT getc_spec @ Π {{ Φ }} -*
  TGT getc_spec @ Π {{ Φ }}.
```

Example 2

$$[\![\mathsf{echo}_{\mathsf{rec}} \oplus \mathsf{getc}_{\mathsf{spec}}]\!] \preceq [\![\mathsf{echo}_{\mathsf{spec}}]\!]$$

```
Lemma sim_getc fns Π_l Π_r PL σi :
  "getc" ↪ None -∗
  PL σi -∗
  ⌜σi.1 ≡ getc_spec⌝ -∗
  ⌜σi.2 = 0⌝ -∗
  □ switch_linked_fixed Tgt Π_l Π_r
    PRE |-∗: σ_l POST, ∃ h v σg, PL σg ∗
    POST (ERCall "getc" [] h) σg |∗: σr Π_r',
  switch_link Tgt Π_r'
    Pre |-∗: σ_r' POST, ∃ h'
    POST (ERReturn (ValNum v) h') _ σ_l |∗: _ Π_l',
      ⌜Π_l' = Π_l⌝ ∗ PL σ_r' ==∗
  ∃ P, P 0 ∗ □ rec_fn_spec_hoare Tgt Π_l "getc" (getc_fn_spec P).
```

Example 2

```
Lemma sim_getc fns Π_l Π_r PL σi :
  "getc" ↪ None -∗
  PL σi -∗
  ⌜σi.1 ≡ getc_spec⌝ -∗
  ⌜σi.2 = 0⌝ -∗
  □ switch Π_l
      PRE |-∗: κ σ0 POST, ∃ h v σg, PL σg ∗
      POST Tgt _ _ |∗:  σi0 Πi, ⌜σi0 = σg⌝ ∗ ⌜Πi = Π_r⌝ ∗
    switch Πi
      PRE |-∗: κ' σ POST0, ∃ e' : rec_ev, ⌜κ' = Some (Incoming, e')⌝ ∗
      POST0 Tgt _ _ |∗: σr Πr, ⌜σr = σ⌝ ∗ ⌜e' = ERCall "getc" [] h⌝ ∗
    switch Πr
      PRE |-∗: κ0 σ1 POST1, ∃ h', ⌜κ0 = Some (Outgoing, ERReturn v h')⌝ ∗
      POST1 Tgt _ _ |∗: σi1 Πi0, ⌜σi1 = σ0⌝ ∗
    switch Πi0
      PRE |-∗: κ'0 σ2 POST2, ∃ e'0, ⌜κ'0 = Some (Incoming, e'0)⌝ ∗
      POST2 Tgt _ _ |∗: σr0 Πr0,
        ⌜σr0 = σ2⌝ ∗ ⌜e'0 = ERReturn v h'⌝ ∗ ⌜Πr0 = Π_l⌝ ∗ PL σ1 ==∗
  ∃ P, P 0 ∗ □ rec_fn_spec_hoare Tgt Π_l "getc" (getc_fn_spec P).
```

Outcome & Takeaways

- Lemma for `TCallRet`
- Keep Πs the same - new lemmas for linking
- Balance between Abstraction and Information
- Balance between Hacking and Thinking