1 *Overture* SYNTAX AND SEMANTICS

$$v \in \mathbb{F}_p,\;\; w \in \text{String},\;\; \iota \in \text{Clients} \subset \mathbb{N}$$

$$\begin{array}{rcll}
\varepsilon & ::= & \mathtt{r}[w] \mid \mathtt{s}[w] \mid \mathtt{m}[w] \mid \mathtt{p}[w] \mid & \textit{expressions} \\
 & & v \mid \varepsilon - \varepsilon \mid \varepsilon + \varepsilon \mid \varepsilon * \varepsilon & \\
x & ::= & \mathtt{r}[w]@\iota \mid \mathtt{s}[w]@\iota \mid \mathtt{m}[w]@\iota \mid \mathtt{p}[w] \mid \mathtt{out}@\iota & \textit{variables} \\
\pi & ::= & \mathtt{m}[w]@\iota := \varepsilon@\iota \mid \mathtt{p}[w] := e@\iota \mid \mathtt{out}@\iota := \varepsilon@\iota \mid \pi;\pi & \textit{protocols}
\end{array}$$

$$\begin{array}{rcl}
[\![\sigma, v]\!]_\iota & = & v \\
[\![\sigma, \varepsilon_1 + \varepsilon_2]\!]_\iota & = & [\![[\![\sigma, \varepsilon_1]\!]_\iota + [\![\sigma, \varepsilon_2]\!]_\iota]\!] \\
[\![\sigma, \varepsilon_1 - \varepsilon_2]\!]_\iota & = & [\![[\![\sigma, \varepsilon_1]\!]_\iota - [\![\sigma, \varepsilon_2]\!]_\iota]\!] \\
[\![\sigma, \varepsilon_1 * \varepsilon_2]\!]_\iota & = & [\![[\![\sigma, \varepsilon_1]\!]_\iota * [\![\sigma, \varepsilon_2]\!]_\iota]\!] \\
[\![\sigma, \mathtt{r}[w]]\!]_\iota & = & \sigma(\mathtt{r}[w]@\iota) \\
[\![\sigma, \mathtt{s}[w]]\!]_\iota & = & \sigma(\mathtt{s}[w]@\iota) \\
[\![\sigma, \mathtt{m}[w]]\!]_\iota & = & \sigma(\mathtt{m}[w]@\iota) \\
[\![\sigma, \mathtt{p}[w]]\!]_\iota & = & \sigma(\mathtt{p}[w])
\end{array}$$

$$(\sigma, x := \varepsilon@\iota) \Rightarrow \sigma\{x \mapsto [\![\sigma, \varepsilon]\!]_\iota\} \qquad \frac{(\sigma_1, \pi_1) \Rightarrow \sigma_2 \qquad (\sigma_2, \pi_2) \Rightarrow \sigma_3}{(\sigma_1, \pi_1; \pi_2) \Rightarrow \sigma_3}$$

2 *Overture* CONSTRAINT TYPING

2.1 Constraint Satisfiability Modulo Finite Fields

$$\begin{array}{rcl}
\phi & ::= & x \mid \phi + \phi \mid \phi - \phi \mid \phi * \phi \\
E & ::= & \phi \equiv \phi \mid E \wedge E
\end{array}$$

We write $E_1 \models E_2$ iff every model of E_1 is a model of E_2. Note that this relation is reflexive and transitive.

$$\lfloor x \rfloor = x \qquad \lfloor \varepsilon_1 + \varepsilon_2 @\iota \rfloor = \lfloor \varepsilon_2 @\iota \rfloor + \lfloor \varepsilon_1 @\iota \rfloor \qquad \lfloor \varepsilon_1 - \varepsilon_2 @\iota \rfloor = \lfloor \varepsilon_2 @\iota \rfloor - \lfloor \varepsilon_1 @\iota \rfloor$$

$$\lfloor \varepsilon_1 * \varepsilon_2 @\iota \rfloor = \lfloor \varepsilon_2 @\iota \rfloor * \lfloor \varepsilon_1 @\iota \rfloor$$

$$\lfloor \mathtt{OT}(\varepsilon_1 @\iota_1, \varepsilon_2, \varepsilon_3)@\iota_2 \rfloor = (\lfloor \varepsilon_1 @\iota_1 \rfloor \wedge \lfloor \varepsilon_3 @\iota_2 \rfloor) \vee (\neg \lfloor \varepsilon_1 @\iota_1 \rfloor \wedge \lfloor \varepsilon_2 @\iota_2 \rfloor)$$

$$\lfloor x := \varepsilon @\iota \rfloor = x \equiv \lfloor \varepsilon @\iota \rfloor \qquad \lfloor \pi_1; \pi_2 \rfloor = \lfloor \pi_1 \rfloor \wedge \lfloor \pi_2 \rfloor$$

The motivating idea is that we can interpret any protocol π as a set of equality constraints $\lfloor \pi \rfloor$ and use an SMT solver to verify properties relevant to correctness, confidentiality, and integrity. Further, we can leverage entailment relation is critical for efficiency– we can use annotations to obtain a weakened precondition for relevant properties. That is, given π, program annotations or other cues can be used to find a minimal E with $\lfloor \pi \rfloor \models E$ for verifying correctness and security.

2.1.1 *Example: Correctness of 3-Party Addition.*

$$
\begin{array}{lcl}
\texttt{m[}s1\texttt{]@2} & := & (\texttt{s[1]} - \texttt{r[local]} - \texttt{r[}x\texttt{]})\texttt{@1} \\
\texttt{m[}s1\texttt{]@3} & := & \texttt{r[}x\texttt{]@1} \\
\texttt{m[}s2\texttt{]@1} & := & (\texttt{s[2]} - \texttt{r[local]} - \texttt{r[}x\texttt{]})\texttt{@2} \\
\texttt{m[}s2\texttt{]@3} & := & \texttt{r[}x\texttt{]@2} \\
\texttt{m[}s3\texttt{]@1} & := & (\texttt{s[3]} - \texttt{r[local]} - \texttt{r[}x\texttt{]})\texttt{@3} \\
\texttt{m[}s3\texttt{]@2} & := & \texttt{r[}x\texttt{]@3} \\
\texttt{p[1]} & := & (\texttt{r[local]} + \texttt{m[}s2\texttt{]} + \texttt{m[}s3\texttt{]})\texttt{@1} \\
\texttt{p[2]} & := & (\texttt{m[}s1\texttt{]} + \texttt{r[local]} + \texttt{m[}s3\texttt{]})\texttt{@2} \\
\texttt{p[3]} & := & (\texttt{m[}s1\texttt{]} + \texttt{m[}s2\texttt{]} + \texttt{r[local]})\texttt{@3} \\
\texttt{out@1} & := & (\texttt{p[1]} + \texttt{p[2]} + \texttt{p[3]})\texttt{@1} \\
\texttt{out@2} & := & (\texttt{p[1]} + \texttt{p[2]} + \texttt{p[3]})\texttt{@2} \\
\texttt{out@3} & := & (\texttt{p[1]} + \texttt{p[2]} + \texttt{p[3]})\texttt{@3}
\end{array}
$$

Letting π be this protocol, we can verify correctness as:

$$\lfloor \pi \rfloor \models \texttt{out@3} \equiv \texttt{s[1]@1} + \texttt{s[2]@2} + \texttt{s[3]@3}$$

2.2 Confidentiality Types

$$
\begin{array}{lcl}
t & ::= & x \mid c(x, T) \\
T & \in & 2^t \\
\Gamma & ::= & \varnothing \mid \Gamma; x : T
\end{array}
$$

Definition 2.1. $R_1; R_2 = R_1 \cup R_2$ iff $R_1 \cap R_2 = \varnothing$.

$$\textsc{DepTy}\quad \varnothing, E \vdash \phi : \mathit{vars}(\phi)$$

$$\textsc{Encode}\quad \frac{E \models \phi \equiv \phi' \oplus \texttt{r[}w\texttt{]@}\iota \qquad \oplus \in \{+, -\} \qquad R, E \vdash \phi' : T}{R; \{\texttt{r[}w\texttt{]@}\iota\}, E \vdash \phi : \{c(\texttt{r[}w\texttt{]@}\iota, T)\}}$$

$$\textsc{Send}\quad \frac{R, E \vdash \lfloor \varepsilon @\iota \rfloor : T}{R, E \vdash x := \varepsilon @\iota : (x : T)}
\qquad
\textsc{Seq}\quad \frac{R_1, E \vdash \pi_1 : \Gamma_1 \qquad R_2, E \vdash \pi_2 : \Gamma_2}{R_1; R_2, E \vdash \pi_1; \pi_2 : \Gamma_1; \Gamma_2}$$

Definition 2.2. $R, E \vdash \pi : \Gamma$ is *valid* iff it is derivable and $\lfloor \pi \rfloor \models E$.

$$\frac{\iota \in C}{\Gamma, C \vdash_{leak} \Gamma(\texttt{m[}w\texttt{]@}\iota)}
\qquad
\frac{\Gamma, C \vdash_{leak} T_1 \cup T_2}{\Gamma, C \vdash_{leak} T_1}
\qquad
\frac{\Gamma, C \vdash_{leak} \{\texttt{m[}w\texttt{]@}\iota\}}{\Gamma, C \vdash_{leak} \Gamma(\texttt{m[}w\texttt{]@}\iota)}$$

$$\frac{\Gamma, C \vdash_{leak} \{\texttt{r[}w\texttt{]@}\iota\} \qquad \Gamma, C \vdash_{leak} \{c(\texttt{r[}w\texttt{]@}\iota, T)\}}{\Gamma, C \vdash_{leak} T}$$

THEOREM 2.3. *If $R, E \vdash \pi : \Gamma$ is valid and there exists no H, C and $\texttt{s[}w\texttt{]@}\iota$ for $\iota \in H$ with $\Gamma, C \vdash_{leak} \{\texttt{s[}w\texttt{]@}\iota\}$, then π satisfies gradual release.*

2.2.1 *Examples.*

```
m[s1]@2 := (s[1] - r[local] - r[x])@1
m[s1]@3 := r[x]@1

// m[s1]@2 : { c(r[x]@1, { c(r[local]@1, {s[1]@1} ) }
// m[s1]@3 : { r[x]@1 }
```

```
m[x]@1 := s2(s[x],-r[x],r[x])@2

// m[x]@1 == s[x]@2 + -r[x]@2
// m[x]@1 : { c(r[x]@2, { s[x]@2 }) }

m[y]@1 := OT(s[y]@1,-r[y],r[y])@2

// m[y]@1 == s[y]@1 + -r[y]@2
// m[y]@1 : { c(r[y]@2, { s[y]@1 }) }
```

3 *Overture* ADVERSARIAL SEMANTICS

$$\begin{array}{lcll} (\sigma, x := \varepsilon @\iota) & \Rightarrow_{\mathcal{A}} & \sigma\{x \mapsto [\![\sigma, \varepsilon]\!]_\iota\} & \iota \in H \\ (\sigma, x := \varepsilon @\iota) & \Rightarrow_{\mathcal{A}} & \sigma\{x \mapsto [\![\mathit{rewrite}_{\mathcal{A}}(\sigma_C, \varepsilon)]\!]_\iota\} & \iota \in C \end{array}$$

$$\begin{array}{rcll} (\sigma, \mathtt{assert}(\varepsilon_1 = \varepsilon_2)@\iota) & \Rightarrow_{\mathcal{A}} & \sigma & \text{if } [\![\sigma, \varepsilon_1]\!]_\iota = [\![\sigma, \varepsilon_2]\!]_\iota \text{ or } \iota \in C \\ (\sigma, \mathtt{assert}(\phi(\varepsilon))@\iota) & \Rightarrow_{\mathcal{A}} & \bot & \text{if } \neg\phi(\sigma, [\![\sigma, \varepsilon]\!]_\iota) \end{array}$$

$$\frac{(\sigma_1, \pi_1) \Rightarrow_{\mathcal{A}} \sigma_2 \qquad (\sigma_2, \pi_2) \Rightarrow_{\mathcal{A}} \sigma_3}{(\sigma_1, \pi_1; \pi_2) \Rightarrow_{\mathcal{A}} \sigma_3} \qquad \frac{(\sigma_1, \pi_1) \Rightarrow_{\mathcal{A}} \bot}{(\sigma_1, \pi_1; \pi_2) \Rightarrow_{\mathcal{A}} \bot}$$

$$\frac{(\sigma_1, \pi_1) \Rightarrow_{\mathcal{A}} \sigma_2 \qquad (\sigma_2, \pi_2) \Rightarrow_{\mathcal{A}} \bot}{(\sigma_1, \pi_1; \pi_2) \Rightarrow_{\mathcal{A}} \bot}$$

3.1 Compositional Type Verification in *Prelude*

Note the redefinition of x impacts the definition of T, Γ, ϕ, and E.

$$x \quad ::= \quad \mathtt{r}[e]@e \mid \mathtt{s}[e]@e \mid \mathtt{m}[e]@e \mid \mathtt{p}[e] \mid \mathtt{out}@e$$

$$\ell \in \text{Field}, \;\; y \in \text{EVar}, \;\; f \in \text{FName}$$

$$\begin{array}{rcl} e & ::= & v \mid \mathtt{r}[e] \mid \mathtt{s}[e] \mid \mathtt{m}[e] \mid \mathtt{p}[e] \mid e \; \mathit{binop} \; e \mid \mathtt{let}\; y = e \;\mathtt{in}\; e \mid \\ & & f(e, \ldots, e) \mid \{\ell = e; \ldots; \ell = e\} \mid e.\ell \\ \mathbf{c} & ::= & \mathtt{m}[e]@e := e@e \mid \mathtt{p}[e] := e@e \mid \mathtt{out}@e := e@e \mid \mathtt{assert}(e = e)@e \mid \\ & & f(e, \ldots, e) \mid \mathbf{c}; \mathbf{c} \mid \mathtt{m}[e]@e \;\mathtt{as}\; \phi \\ \mathit{binop} & ::= & + \mid - \mid * \mid {+}{+} \\ v & ::= & w \mid \iota \mid \varepsilon \mid \{\ell = v; \ldots; \ell = v\} \\ \mathit{fn} & ::= & f(y, \ldots, y)\{e\} \mid f(y, \ldots, y)\{\mathbf{c}\} \end{array}$$

$$R \Vdash x : (\varnothing, \{x\}) \qquad \frac{R \Vdash \phi : (R_1, T) \qquad \mathtt{r}[w]@\iota \notin R \qquad \oplus \in \{+, -\}}{R_1 \Vdash \phi \oplus \mathtt{r}[w]@\iota : (R_1 \cup \{\mathtt{r}[w]@\iota\}, \{c(\mathtt{r}[w]@\iota, T)\})}$$

$$\frac{R \Vdash \phi_1 : (R_1, T_1) \qquad R \Vdash \phi_2 : (R_2, T_2) \qquad \oplus \in \{+, -, *\}}{R_1 \Vdash \phi_1 \oplus \phi_2 : (R_1; R_2, T_1 \cup T_2)}$$

$$\frac{e[v/y] \Rightarrow v'}{\texttt{let}\ y = v\ \texttt{in}\ e \Rightarrow v'}$$

$$\frac{C(f) = y_1, \ldots, y_n,\ e \qquad e_1 \Rightarrow v_1 \cdots e_n \Rightarrow v_n \qquad e[v_1/y_1] \cdots [v_n/y_n] \Rightarrow v}{f(e_1, \ldots, e_n) \Rightarrow v}$$

$$\frac{e_1 \Rightarrow v_1 \cdots e_n \Rightarrow v_n}{\{\ell_1 = e_1; \ldots; \ell_n = e_n\} \Rightarrow \{\ell_1 = v_1; \ldots; \ell_n = v_n\}} \qquad \frac{e \Rightarrow \{\ldots; \ell = v; \ldots\}}{e.\ell \Rightarrow v} \qquad \frac{e_1 \Rightarrow w_1 \qquad e_2 \Rightarrow w_2}{e_1 \texttt{++} e_2 \Rightarrow w_1 w_2}$$

$$\textsc{Mesg}\ \frac{e_1 \Rightarrow \varepsilon \qquad e_2 \Rightarrow \iota \qquad R_1 \Vdash \lfloor \varepsilon @ \iota \rfloor : (R_2, T)}{R_1 \vdash x := e_1 @ e_2 : \{E\}\ x : T, R_1; R_2\ \{E \wedge x \equiv \lfloor \varepsilon @ \iota \rfloor\}}$$

$$\textsc{Encode}\ \frac{e_1 \Rightarrow w \qquad e_2 \Rightarrow \iota \qquad E \models \lfloor \varepsilon @ \iota \rfloor \equiv \phi \qquad R_1 \Vdash \phi : (R_2, T)}{R_1 \vdash \texttt{m[}e_1\texttt{]@}e_2\ \texttt{as}\ \phi : \{E\}\ \texttt{m[}w\texttt{]@}\iota : T, R_1; R_2\ \{E \wedge \texttt{m[}w\texttt{]@}i \equiv \phi\}}$$

$$\textsc{App}\ \frac{\begin{array}{c}\mathrm{sig}(f) = \Pi x_1, \ldots, x_n.\{E_1\}\ \Gamma, R\ \{E_2\} \\ e_1 \Rightarrow v_1\ \cdots\ e_n \Rightarrow v_n \qquad \rho = [v_1/x_1] \cdots [v_n/x_n] \qquad E \models \rho(E_1)\end{array}}{R_1 \vdash f(e_1, \ldots, e_n) : \{E\}\ \rho(\Gamma), R_1; \rho(R)\ \{E \wedge \rho(E_2)\}}$$

$$\textsc{Seq}\ \frac{R_1 \vdash \pi_1 : \{E_1\}\ \Gamma_2, R_2\ \{E_2\} \qquad R_1 \vdash \pi_2 : \{E_2\}\ \Gamma_3, R_3\ \{E_3\}}{R_1 \vdash \pi_1; \pi_2 : \{E_1\}\ \Gamma_2; \Gamma_3, R_2; R_3\ \{E_3\}}$$

$$\textsc{Sig}\ \frac{\begin{array}{c}C(f) = x_1, \ldots, x_n, \mathbf{c} \\ \rho = [v_1/x_1] \cdots [v_n/x_n] \qquad \varnothing \vdash \rho(\mathbf{c}) : \{\rho(E_1)\}\ \rho(\Gamma), \rho(R)\ \{E\} \qquad E \models \rho(E_2)\end{array}}{f : \Pi x_1, \ldots, x_n.\{E_1\}\ \Gamma, R\ \{E_2\}}$$

Definition 3.1. sig is *verified* iff $f : \mathrm{sig}(f)$ is valid for all $f \in \mathrm{dom}(\mathrm{sig})$.

The following theorem holds for protocols with default preprocessing.

Theorem 3.2. *If* sig *is verified and* $\varnothing \vdash e : \{\varnothing\}\ \Gamma, R\ \{E\}$ *then* $e \Rightarrow \pi$ *and* $R, E \vdash \pi : \Gamma$ *is valid.*

3.1.1 *Examples.*

```
andtableygc(g,x,y)
{
  let table = (~r[g],~r[g],~r[g],r[g])
  in permute4(r[x],r[y],table)
}

m[x]@1 := s2(s[x],r[x],~r[x])@2;
m[x]@1 as s[x]@2 xor r[x]@2;

// m[x]@1 : { c(r[x]@2, { s[x]@2 }) }
```

```
m[y]@1 := OT(s[y]@1,r[y],~r[y])@2;
m[y]@1 as s[y]@1 xor r[y]@2;

// m[y]@1 : { c(r[y]@2, { s[y]@1 }) }

m[ag]@1 := OT4(m[x]@1, m[y]@1, andtable(ag,r[x],r[y]))@2;
m[ag]@1 as  ~((r[x]@2 = m[x]@1) and (r[y]@2 = m[y]@1)) xor r[ag]@2;

// m[ag]@1 : { c(r[ag]@2, {r[x]@2, r[y]@2, m[x]@1,  m[y]@1} }

p[o] := OT2(m[ag]@1, perm2(r[ag],(false,true)))@2

// p[o] : { c(r[ag]@2, {r[x]@2, r[y]@2,  m[x]@1,  m[y]@1}), r[ag]@2  }

out@1 := p[o]@1

// out@1 == s[x] and s[y]

    encodegmw(in, i1, i2) {
      m[in]@i2 := (s[in] xor r[in])@i1;
      m[in]@i1 := r[in]@i1
    }

    andtablegmw(x, y, z) {
      let r11 = r[z] xor (m[x] xor true) and (m[y] xor true) in
      let r10 = r[z] xor (m[x] xor true) and (m[y] xor false) in
      let r01 = r[z] xor (m[x] xor false) and (m[y] xor true) in
      let r00 = r[z] xor (m[x] xor false) and (m[y] xor false) in
      { row1 = r11; row2 = r10; row3 = r01; row4 = r00 }
    }

    andgmw(z, x, y) {
      let table = andtablegmw(x,y,z) in
      m[z]@2 := OT4(m[x],m[y],table,2,1);
      m[z]@2 as ~((m[x]@1 xor m[x]@2) and (m[y]@1 xor m[y]@2)) xor r[z]@1);
      m[z]@1 := r[z]@1
    }

    // and gate correctness postcondition
   {} andgmw { m[z]@1 xor m[z]@2 == (m[x]@1 xor m[x]@2) and (m[y]@1 xor m[y]@2) }

    // and gate type
    andgmw :
     Pi z,x,y .
     {}
     { { r[z]@1 },
     (m[z]@1 : { r[z]@1 }; m[z]@2 : {c(r[z]@1, { m[x]@1, m[x]@2, m[y]@1, m[y]@2 })} ),
```

```
    m[z]@1 xor m[z]@2 == (m[x]@1 xor m[x]@2) and (m[y]@1 xor m[y]@2)}

xorgmw(z, x, y) {
  m[z]@1 := (m[x] xor m[y])@1; m[z]@2 := (m[x] xor m[y])@2;
}

decodegmw(z) {
  p["1"] := m[z]@1; p["2"] := m[z]@2;
  out@1 := (p["1"] xor p["2"])@1;
  out@2 := (p["1"] xor p["2"])@2
}

prot() {
  encodegmw("x",2,1);
  encodegmw("y",2,1);
  encodegmw("z",1,2);
  andgmw("g1","x","z");
  xorgmw("g2","g1","y");
  decodegmw("g2")
}

{} prot { out@1 == (s["x"]@1 and s["z"]@2) xor s["y"]@1 }
```

3.2 Integrity Types

$$\textsc{Value}\quad \Gamma, \varnothing, E \vdash_\iota v : \varnothing \cdot \mathrm{High}$$

$$\textsc{Secret}\quad \Gamma, \varnothing, E \vdash_\iota \mathtt{s}[w] : \{\mathtt{s}[w]@\iota\} \cdot \mathcal{L}(\iota)$$

$$\textsc{Rando}\quad \Gamma, \varnothing, E \vdash_\iota \mathtt{r}[w] : \{\mathtt{r}[w]@\iota\} \cdot \mathcal{L}(\iota)$$

$$\textsc{Mesg}\quad \Gamma, \varnothing, E \vdash_\iota \mathtt{m}[w] : \Gamma(\mathtt{m}[w]@\iota)$$

$$\textsc{PubM}\quad \Gamma, \varnothing, E \vdash_\iota \mathtt{p}[w] : \Gamma(\mathtt{p}[w])$$

$$\textsc{IntegrityWeaken}\quad \frac{\Gamma, R, E \vdash_\iota \varepsilon : T \cdot \varsigma_1 \qquad \varsigma_1 \preceq \varsigma_2}{\Gamma, R, E \vdash_\iota \varepsilon : T \cdot \varsigma_2}$$

$$\textsc{Encode}\quad \frac{\Gamma, \varnothing, E \vdash_\iota \varepsilon : T \cdot \varsigma \qquad E \models \lfloor \varepsilon@\iota \rfloor = \phi \oplus \mathtt{r}[w]@\iota' \qquad \oplus \in \{+, -\}}{\Gamma, \mathtt{r}[w]@\iota, E \vdash_\iota \varepsilon : \{c(\mathtt{r}[w]@\iota', \Gamma(\phi))\} \cdot \varsigma}$$

$$\textsc{Binop}\quad \frac{\Gamma, R_1, E \vdash_\iota \varepsilon_1 : T_1 \cdot \varsigma \qquad \Gamma, R_2, E \vdash_\iota \varepsilon_2 : T_2 \cdot \varsigma \qquad \oplus \in \{+, -, *\}}{\Gamma, R_1; R_2, E \vdash_\iota \varepsilon_1 \oplus \varepsilon_2 : T_1 \cup T_2 \cdot \varsigma}$$

$$\textsc{Send}\quad \frac{\Gamma, R, E \vdash_\iota \varepsilon : T \cdot \mathcal{L}(\iota) \qquad E' \models E \wedge x = \lfloor \varepsilon @ \iota \rfloor}{\Gamma, R, E \vdash x := \varepsilon @ \iota : \Gamma; x : T \cdot \mathcal{L}(\iota), E'}$$

$$\textsc{Assert}\quad \frac{E \models \lfloor \varepsilon_1 @ \iota \rfloor = \lfloor \varepsilon_2 @ \iota \rfloor}{\Gamma, R, E \vdash \mathtt{assert}(\varepsilon_1 = \varepsilon_2) @ \iota : \Gamma, E}$$

$$\textsc{Seq}\quad \frac{\Gamma_1, R_1, E_1 \vdash \pi_1 : \Gamma_2, E_2 \qquad \Gamma_2, R_2, E_2 \vdash \pi_2 : \Gamma_3, E_3}{\Gamma_1, R_1; R_2, E_1 \vdash \pi_1; \pi_2 : \Gamma_3, E_3}$$

$$\textsc{Constraint}\quad \frac{\Gamma_1, R, E_1 \vdash \pi : \Gamma_2, E_2 \qquad E_1' \models E_1 \qquad E_2 \models E_2'}{\Gamma_1, R, E_1' \vdash \pi : \Gamma_2, E_2'}$$

$$\text{MAC}\quad \frac{E \models \mathtt{m[}wm\mathtt{]}@\iota = \mathtt{m[}wk\mathtt{]}@\iota + (\mathtt{m[delta]}@\iota * \mathtt{m[}ws\mathtt{]}@\iota) \qquad \Gamma(\mathtt{m[}ws\mathtt{]}@\iota) = T \cdot \varsigma}{\Gamma, R, E \vdash \mathtt{assert(m[}wm\mathtt{]} = \mathtt{m[}wk\mathtt{]} + (\mathtt{m[delta]} * \mathtt{m[}ws\mathtt{]}))@\iota : \Gamma; \mathtt{m[}ws\mathtt{]}@\iota : T \cdot \mathrm{High}, E}$$

4 *Prelude* SYNTAX AND SEMANTICS

$$\ell \in \text{Field}, \ y \in \text{EVar}, \ f \in \text{FName}$$

$$\begin{array}{rcl}
e & ::= & v \mid \mathtt{r[}e\mathtt{]} \mid \mathtt{s[}e\mathtt{]} \mid \mathtt{m[}e\mathtt{]} \mid \mathtt{p[}e\mathtt{]} \mid e \ \mathit{binop}\ e \mid \mathtt{let}\ y = e\ \mathtt{in}\ e \mid \\
 & & f(e, \ldots, e) \mid \{\ell = e; \ldots; \ell = e\} \mid e.\ell \\
\mathbf{c} & ::= & \mathtt{m[}e\mathtt{]}@e := e@e \mid \mathtt{p[}e\mathtt{]} := e@e \mid \mathtt{out}@e := e@e \mid \mathtt{assert}(e = e)@e \mid \\
 & & f(e, \ldots, e) \mid \mathbf{c}; \mathbf{c} \mid \mathtt{pre}(E) \mid \mathtt{post}(E) \\
\mathit{binop} & ::= & + \mid - \mid * \mid \mathtt{++} \\
v & ::= & w \mid \iota \mid \varepsilon \mid \{\ell = v; \ldots; \ell = v\} \\
\mathit{fn} & ::= & f(y, \ldots, y)\{e\} \mid f(y, \ldots, y)\{\mathbf{c}\} \\
\phi & ::= & \mathtt{r[}e\mathtt{]}@e \mid \mathtt{s[}e\mathtt{]}@e \mid \mathtt{m[}e\mathtt{]}@e \mid \mathtt{p[}e\mathtt{]} \mid \mathtt{out}@e \mid \phi + \phi \mid \phi - \phi \mid \phi * \phi \\
E & ::= & \phi \equiv \phi \mid E \wedge E
\end{array}$$

$$\frac{e[v/y] \Rightarrow v'}{\mathtt{let}\ y = v\ \mathtt{in}\ e \Rightarrow v'}$$

$$\frac{C(f) = y_1, \ldots, y_n,\ e \qquad e_1 \Rightarrow v_1 \cdots e_n \Rightarrow v_n \qquad e[v_1/y_1] \cdots [v_n/y_n] \Rightarrow v}{f(e_1, \ldots, e_n) \Rightarrow v}$$

$$\frac{e_1 \Rightarrow v_1 \cdots e_n \Rightarrow v_n}{\{\ell_1 = e_1; \ldots; \ell_n = e_n\} \Rightarrow \{\ell_1 = v_1; \ldots; \ell_n = v_n\}} \qquad \frac{e \Rightarrow \{\ldots; \ell = v; \ldots\}}{e.\ell \Rightarrow v} \qquad \frac{e_1 \Rightarrow w_1 \qquad e_2 \Rightarrow w_2}{e_1 \mathtt{++} e_2 \Rightarrow w_1 w_2}$$

$$\frac{e_1 \Rightarrow \varepsilon_1 \qquad e_2 \Rightarrow \varepsilon_2 \qquad e \Rightarrow \iota}{(\pi, (E_1, E_2), \mathsf{on}, \mathtt{assert}(e_1 = e_2)\mathtt{@}e) \Rightarrow (\pi; \mathtt{assert}(\varepsilon_1 = \varepsilon_2)\mathtt{@}\iota, (E_1, E_2 \wedge \lfloor \varepsilon_1\mathtt{@}\iota \rfloor = \lfloor \varepsilon_2\mathtt{@}\iota \rfloor), \mathsf{on})}$$

$$\frac{e_1 \Rightarrow \varepsilon_1 \qquad e_2 \Rightarrow \varepsilon_2 \qquad e \Rightarrow \iota}{(\pi, (E_1, E_2), \mathtt{off}, \mathtt{assert}(e_1 = e_2)\mathtt{@}e) \Rightarrow (\pi; \mathtt{assert}(\varepsilon_1 = \varepsilon_2)\mathtt{@}\iota, (E_1, E_2, \mathtt{off})}$$

$$\frac{e_1 \Rightarrow w \qquad e_2 \Rightarrow \iota_1 \qquad e_3 \Rightarrow \varepsilon \qquad e_4 \Rightarrow \iota_2}{(\pi, (E_1, E_2), \mathsf{on}, \mathtt{m[}e_1\mathtt{]@}e_2 := e_3\mathtt{@}e_4) \Rightarrow (\pi; \mathtt{m[}w\mathtt{]@}\iota_1 := \varepsilon\mathtt{@}\iota_2, (E_1 \wedge \mathtt{m[}w\mathtt{]@}\iota_1 = \lfloor \varepsilon\mathtt{@}\iota_2 \rfloor, E_2), \mathsf{on})}$$

$$\frac{e_1 \Rightarrow w \qquad e_2 \Rightarrow \iota_1 \qquad e_3 \Rightarrow \varepsilon \qquad e_4 \Rightarrow \iota_2}{(\pi, (E_1, E_2), \mathtt{off}, \mathtt{m[}e_1\mathtt{]@}e_2 := e_3\mathtt{@}e_4) \Rightarrow (\pi; \mathtt{m[}w\mathtt{]@}\iota_1 := \varepsilon\mathtt{@}\iota_2, (E_1, E_1), \mathtt{off})}$$

$$(\pi, (E_1, E_2), \mathsf{on}, \mathtt{pre}(E)) \Rightarrow (\pi, E_1, E_2 \wedge E, \mathtt{off})$$

$$(\pi, (E_1, E_2), \mathtt{off}, \mathtt{post}(E)) \Rightarrow (\pi, (E_1 \wedge E, E_2), \mathsf{on})$$

$$\frac{(\pi_1, (E_{11}, E_{12}), sw_1, \mathbf{c}_1) \Rightarrow (\pi_2, (E_{21}, E_{22}), sw_2) \qquad (\pi_2, (E_{21}, E_{22}), sw_2, \mathbf{c}_2) \Rightarrow (\pi_3, (E_{31}, E_{32}), sw_3)}{(\pi_1, (E_{11}, E_{12}), sw_1, \mathbf{c}_1; \mathbf{c}_2) \Rightarrow (\pi_3, (E_{31}, E_{32}), sw_3)}$$

$$\frac{\begin{array}{c} C(f) = y_1, \ldots, y_n,\ \mathbf{c} \\ e_1 \Rightarrow v_1 \cdots e_n \Rightarrow v_n \qquad (\pi_1, (E_{11}, E_{12}), sw_1, \mathbf{c}[v_1/y_1,] \cdots [v_n/y_n]) \Rightarrow (\pi_2, (E_{21}, E_{22}), sw_2) \end{array}}{(\pi_1, (E_{11}, E_{12}), sw_1, f(e_1, \ldots, e_n)) \Rightarrow (\pi_2, (E_{21}, E_{22}), sw_2)}$$

5 EXAMPLES

```
secopen(w1,w2,w3,i1,i2) {
    pre(m[w1++"m"]@i2 == m[w1++"k"]@i1 + (m["delta"]@i1 * m[w1++"s"]@i2 /\
        m[w1++"m"]@i2 == m[w1++"k"]@i1 + (m["delta"]@i1 * m[w1++"s"]@i2));
    let locsum =  macsum(macshare(w1), macshare(w2)) in
    m[w3++"s"]@i1 := (locsum.share)@i2;
    m[w3++"m"]@i1 := (locsum.mac)@i2;
    auth(m[w3++"s"],m[w3++"m"],mack(w1) + mack(w2),i1);
    m[w3]@i1 := (m[w3++"s"] + (locsum.share))@i1
}


_open(x,i1,i2){
  m[x++"exts"]@i1 := m[x++"s"]@i2;
  m[x++"extm"]@i1 := m[x++"m"]@i2;
  assert(m[x++"extm"] == m[x++"k"] + (m["delta"] * m[x++"exts"]));
  m[x]@i1 := (m[x++"exts"] + m[x++"s"])@i2
}`

_sum(z, x, y,i1,i2) {
    pre(m[x++"m"]@i2 == m[x++"k"]@i1 + (m["delta"]@i1 * m[x++"s"]@i2 /\
```

```
            m[y++"m"]@i2 == m[y++"k"]@i1 + (m["delta"]@i1 * m[y++"s"]@i2));
        m[z++"s"]@i2 := (m[x++"s"] + m[y++"s"])@i2;
        m[z++"m"]@i2 := (m[x++"m"] + m[y++"m"])@i2;
        m[z++"k"]@i1 := (m[x++"k"] + m[y++"k"])@i1;
        post(m[z++"m"]@i2 == m[z++"k"]@i1 + (m["delta"]@i1 * m[z++"s"]@i2)
    }

    sum(z,x,y) { _sum(z,x,y,1,2);_sum(z,x,y,2,1) }

    open(x) { _open(x,1,2); _open(x,2,1) }


    sum("a","x","d");
    open("d");
    sum("b","y","e");
    open("e");
    let xys =
        macsum(macctimes(macshare("b"), m["d"]),
               macsum(macctimes(macshare("a"), m["e"]),
                      macshare("c")))
    let xyk = mack("b") * m["d"] + mack("a") * m["e"] + mack("c")

    secopen("a","x","d",1,2);
      secopen("a","x","d",2,1);
      secopen("b","y","e",1,2);
      secopen("b","y","e",2,1);
      let xys =
        macsum(macctimes(macshare("b"), m["d"]),
               macsum(macctimes(macshare("a"), m["e"]),
                      macshare("c")))
      in
      let xyk = mack("b") * m["d"] + mack("d") * m["d"] + mack("c")
      in
      secreveal(xys,xyk,"1",1,2);
      secreveal(maccsum(xys,m["d"] * m["e"]),
                xyk - m["d"] * m["e"],
                "2",2,1);
      out@1 := (p[1] + p[2])@1;
      out@2 := (p[1] + p[2])@2;
```