

## A Additional functions

Figure 3 showed the foundational monadic functions `parallel`, `congruently`, `comm`, `enclave`, `naked`, `fanOut`, and `fanIn`. Figure 9 shows type signatures for the entire library (as exported), in alphabetical order. Some functions are “core” in the sense that they can’t be written without reference to MultiChor’s internal machinery. Other functions are “helper functions”, which are implemented entirely using the exposed core functions.

## B Additional Choreographies for the GMW Protocol

**Oblivious transfer.** Our implementation of oblivious transfer leverages a common strategy for building OT from public-key encryption. First, the receiver generates two public keys and one secret key (line 23); one of the public keys is real, and corresponds to the secret key, while the other is chosen at random from the space of public keys and has no corresponding secret key. The select bit determines the ordering of the public keys. The receiver sends the public keys to the sender (lines 24–25); the sender encrypts both  $b_1$  and  $b_2$  with the corresponding public keys and sends the ciphertexts back to the receiver (lines 26–27). Finally, the receiver decrypts the selected value (lines 28–30).

The sender treats both  $b_1$  and  $b_2$  in the same way, and cannot tell which public key is real and which one is fake—so the sender does not learn which value was selected. The receiver gets both encrypted values, but can only decrypt one of them, since only one of the public keys used has a corresponding secret key (the other public key is totally random). This version of OT is secure only against *honest but curious* or *passive* adversaries, who observe network communications but do not change the behavior of the parties, since an actively malicious receiver could create two actual key pairs in the first step of the protocol and thus be able to decrypt both  $b_1$  and  $b_2$  at the end. More complicated variants of the protocol can defend against this kind of attack.

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```

1  (~>) :: forall a l ls' m ps. (Show a, Read a, KnownSymbol l, KnownSymbols ls')
2      => (Member l ps, m a) -> Subset ls' ps -> Choreo ps m (Located ls' a)
3  infix 4 ~>
4
5  (~>) :: forall a l ls' m ps. (Show a, Read a, KnownSymbol l, KnownSymbols ls')
6      => (Member l ps, Unwrap l -> m a) -> Subset ls' ps -> Choreo ps m (Located ls' a)
7  infix 4 ~>
8
9  (@@) :: Member x ys -> Subset xs ys -> Subset (x ': xs) ys
10 infixr 5 @@
11
12 (~>) :: (Show a, Read a, KnownSymbol l, KnownSymbols ls', CanSend s l a ls ps w)
13     => s -- ^ The message argument can take three forms:
14         --   `(Member sender census, wrapped owners a)` where
15         --   the sender is explicitly listed in owners,
16         --   `(Member sender owners, Subset owners census, wrapped owners a)`, or
17         --   `(Member sender census, (Member sender owners, wrapped owners a)`.
18     -> Subset ls' ps -> Choreo ps m (Located ls' a)
19 infix 4 ~>
20
21 allof :: forall ps. Subset ps ps
22
23 Backend :: Type -> Constraint -- A phonebook for running Network monad expressions.
24
25 broadcast :: forall l a ps ls w m s.
26     (Show a, Read a, KnownSymbol l, KnownSymbols ps, CanSend s l a ls ps w)
27     => s -> Choreo ps m a
28
29 Choreo :: [LocTy] -> (Type -> Type) -> Type -> Type
30 type Choreo ps m = Freer (ChoreoSig ps m)
31
32 comm :: (Show a, Read a, KnownSymbol l, KnownSymbols ls', Wrapped w)
33     => Member l ps -> (Member l ls, w ls a) -> Subset ls' ps
34     -> Choreo ps m (Located ls' a)
35 infix 4 `comm`
36
37 cond :: (KnownSymbols ls)
38     => (Subset ls ps, (Subset ls qs, Located qs a)) -> (a -> Choreo ls m b)
39     -> Choreo ps m (Located ls b)
40
41 congruently :: (KnownSymbols ls)
42     => Subset ls ps -> (Unwraps ls -> a) -> Choreo ps m (Located ls a)
43 infix 4 `congruently`
44
45 consSet :: Subset xs (x ': xs)
46
47 consSub :: Subset xs ys -> Member x ys -> Subset (x ': xs) ys
48
49 consSuper :: forall xs ys y. Subset xs ys -> Subset xs (y ': ys)

```

Figure 9. The MultiChor API, part 1/4.

```

50  enclave :: (KnownSymbols ls)
51          => Subset ls ps -> Choreo ls m a -> Choreo ps m (Located ls a)
52  infix 4 `enclave`
53
54  enclaveTo :: forall ls a rs ps m. (KnownSymbols ls)
55            => Subset ls ps -> Subset rs ls -> Choreo ls m (Located rs a)
56            -> Choreo ps m (Located rs a)
57  infix 4 `enclaveTo`
58
59  enclaveToAll :: forall ls a ps m. (KnownSymbols ls)
60               => Subset ls ps -> Choreo ls m (Located ls a) -> Choreo ps m (Located ls a)
61  infix 4 `enclaveToAll`
62
63  epp :: (Monad m) => Choreo ps m a -> LocTm -> Network m a
64
65  ExplicitMember :: forall k. k -> [k] -> Constraint
66  explicitMember :: forall k (x :: k) (xs :: [k]). ExplicitMember x xs => Member x xs
67
68  ExplicitSubset :: forall {k}. [k] -> [k] -> Constraint
69  explicitSubset :: forall {k} (xs :: [k]) (ys :: [k]). ExplicitSubset xs ys => Subset xs ys
70
71  Faceted :: [LocTy] -> Type -> Type
72
73  fanIn :: (KnownSymbols qs, KnownSymbols rs)
74          => Subset qs ps -> Subset rs ps
75          -> (forall q. (KnownSymbol q)
76              => Member q qs -> Choreo ps m (Located rs a))
77          -> Choreo ps m (Located rs [a])
78
79  fanOut :: (KnownSymbols qs, Wrapped w)
80           => Subset qs ps
81           -> (forall q. (KnownSymbol q) => Member q qs -> Choreo ps m (w '[q] a))
82           -> Choreo ps m (Faceted qs a)
83
84  flatten :: Subset ls ms -> Subset ls ns -> Located ms (Located ns a)
85           -> Located ls a
86  infix 3 `flatten`
87
88  fracture :: forall ls a. (KnownSymbols ls) => Located ls a -> Faceted ls a
89
90  inSuper :: Subset xs ys -> Member x xs -> Member x ys
91
92  IsMember :: forall k. k -> [k] -> Type
93
94  IsSubset :: forall k. [k] -> [k] -> Type
95
96  KnownSymbols :: [Symbol] -> Constraint -- lift KnownSymbol to type-level lists
97
98  listedFifth :: forall p5 p4 p3 p2 p1 ps. Member p5 (p1 ': p2 ': p3 ': p4 ': p5 ': ps)
99
100 listedFirst :: forall p1 ps. Member p1 (p1 ': ps)
101
102 listedForth :: forall p4 p3 p2 p1 ps. Member p4 (p1 ': p2 ': p3 ': p4 ': ps)
103
104 listedSecond :: forall p2 p1 ps. Member p2 (p1 ': p2 ': ps)

```

Figure 9. The MultiChor API, part 2/4.

```

1761 105 listedSixth :: forall p6 p5 p4 p3 p2 p1 ps. Member p6 (p1 ': p2 ': p3 ': p4 ': p5 ': p6 ': ps)
1762 106
1763 107 listedThird :: forall p3 p2 p1 ps. Member p3 (p1 ': p2 ': p3 ': ps)
1764 108
1765 109 localize :: (KnownSymbol l) => Member l ls -> Faceted ls a -> Located '[1] a
1766 110
1767 111 locally :: (KnownSymbol (l :: LocTy))
1768 112         => Member l ps -> (Unwrap l -> m a) -> Choreo ps m (Located '[1] a)
1769 113 infix 4 `locally`
1770 114
1771 115 locally_ :: (KnownSymbol l) => Member l ps -> (Unwrap l -> m ()) -> Choreo ps m ()
1772 116 infix 4 `locally_`
1773 117
1774 118 _locally :: (KnownSymbol l) => Member l ps -> m a -> Choreo ps m (Located '[1] a)
1775 119 infix 4 `_locally`
1776 120
1777 121 _locally_ :: (KnownSymbol l) => Member l ps -> m () -> Choreo ps m ()
1778 122 infix 4 `_locally_`
1779 123
1780 124 Located :: [LocTy] -> Type -> Type
1781 125
1782 126 LocTm :: Type
1783 127 type LocTm = String
1784 128
1785 129 LocTy :: Type
1786 130 type LocTy = Symbol
1787 131
1788 132 Member :: forall {k}. k -> [k] -> Type
1789 133 type Member x xs = Proof (IsMember x xs)
1790 134
1791 135 mkLoc :: String -> Q [Dec] -- Template Haskell
1792 136
1793 137 naked :: Subset ps qs -> Located qs a -> Choreo ps m a
1794 138 infix 4 `naked`
1795 139
1796 140 Network :: (Type -> Type) -> Type -> Type
1797 141
1798 142 NetworkSig :: (Type -> Type) -> Type -> Type
1799 143
1800 144 nobody :: Subset '[] ys
1801 145
1802 146 parallel :: (KnownSymbols ls)
1803 147         => Subset ls ps -> (forall l. (KnownSymbol l) => Member l ls -> Unwrap l -> m a)
1804 148         -> Choreo ps m (Faceted ls a)
1805 149
1806 150 parallel_ :: forall ls ps m. (KnownSymbols ls)
1807 151         => Subset ls ps -> (forall l. (KnownSymbol l) => Member l ls -> Unwrap l -> m ())
1808 152         -> Choreo ps m ()
1809 153
1810 154 _parallel :: forall ls a ps m. (KnownSymbols ls)
1811 155         => Subset ls ps -> m a -> Choreo ps m (Faceted ls a)
1812 156
1813 157 recv :: forall a (m :: Type -> Type). Read a => LocTm -> Network m a
1814 158
1815 159 run :: forall (m :: Type -> Type) a. m a -> Network m a

```

Figure 9. The MultiChor API, part 3/4.

```

160 runChoreo :: forall ps b m. Monad m => Choreo ps m b -> m b
161
162 runNetwork :: (Backend c, MonadIO m) => c -> LocTm -> Network m a -> m a
163
164 send :: forall a (m :: Type -> Type). Show a => a -> [LocTm] -> Network m ()
165
166 singleton :: forall p. Member p (p ': '[])
167
168 Subset :: forall {k}. [k] -> [k] -> Type
169 type Subset xs ys = Proof (IsSubset xs ys)
170
171 toLocs :: forall (ls :: [LocTy]) (ps :: [LocTy]). KnownSymbols ls => Subset ls ps -> [LocTm]
172
173 toLocTm :: forall (l :: LocTy) (ps :: [LocTy]). KnownSymbol l => Member l ps -> LocTm
174
175 Unwrap :: LocTy -> Type
176 type Unwrap (l :: LocTy) = forall ls a w. (Wrapped w) => Member l ls -> w ls a -> a
177
178 Unwraps :: [LocTy] -> Type
179 type Unwraps (qs :: [LocTy]) = forall ls a. Subset qs ls -> Located ls a -> a
180
181 Wrapped :: ([Symbol] -> Type -> Type) -> Constraint

```

Figure 9. The MultiChor API, part 4/4.

```

1  genKeys :: (CRT.MonadRandom m) => Bool -> m (RSA.PublicKey, RSA.PublicKey, RSA.PrivateKey)
2  genKeys s = do -- Generate keys for OT. One key is real, and one is fake - select bit decides
3    (pk, sk) <- genKeyPair
4    fakePk <- generateFakePK
5    return $ if s then (pk, fakePk, sk) else (fakePk, pk, sk)
6
7  encryptS :: (CRT.MonadRandom m) => -- Encryption based on select bit
8    (RSA.PublicKey, RSA.PublicKey) -> Bool -> Bool -> m (ByteString, ByteString)
9  encryptS (pk1, pk2) b1 b2 = do c1 <- encryptRSA pk1 b1; c2 <- encryptRSA pk2 b2; return (c1, c2)
10
11 decryptS :: (CRT.MonadRandom m) => -- Decryption based on select bit
12    (RSA.PublicKey, RSA.PublicKey, RSA.PrivateKey) -> Bool -> (ByteString, ByteString) -> m Bool
13 decryptS (_, _, sk) s (c1, c2) = if s then decryptRSA sk c1 else decryptRSA sk c2
14
15 -- One out of two OT
16 ot2 :: (KnownSymbol sender, KnownSymbol receiver, MonadIO m, CRT.MonadRandom m) =>
17   Located '[sender] (Bool, Bool) -> Located '[receiver] Bool
18   -> Choreo '[sender, receiver] (CLI m) (Located '[receiver] Bool)
19 ot2 bb s = do
20   let sender = listedFirst :: Member sender '[sender, receiver]
21   let receiver = listedSecond :: Member receiver '[sender, receiver]
22
23   keys <- receiver `locally` \un -> liftIO $ genKeys $ un singleton s
24   pks <- (receiver, \un -> let (pk1, pk2, _) = un singleton keys
25     in return (pk1, pk2)) ~~> sender @@ nobody
26   encrypted <- (sender, \un -> let (b1, b2) = un singleton bb
27     in liftIO $ encryptS (un singleton pks) b1 b2) ~~> receiver @@ nobody
28   receiver `locally` \un -> liftIO $ decryptS (un singleton keys)
29     (un singleton s)
30     (un singleton encrypted)

```

**Figure 10.** A choreography for performing 1 out of 2 oblivious transfer (OT) using RSA public-key encryption. The choreography involves exactly two parties, `sender` and `receiver`.