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1  ---------- MODULE CC ----------
   TLA+ specification of Causal Consistency variants, including CC, CM, and CCv.
   See the paper "On Verifying Causal Consistency" (POPL'2017).
8  EXTENDS Naturals, Sequences, FiniteSets, Functions, FiniteSetsExt, RelationUtils, TLC

10 CONSTANTS Keys, Vals
11 InitVal ≜ CHOOSE v : v ∉ (Keys ∪ Vals)

13  oid: unique operation identifier
14 Operation ≜ [op : {"read", "write"}, key : Keys, val : Vals, oid : Nat]
15 R(k, v, oid) ≜ [op ↦ "read", key ↦ k, val ↦ v, oid ↦ oid]
16 W(k, v, oid) ≜ [op ↦ "write", key ↦ k, val ↦ v, oid ↦ oid]

18 Session ≜ Seq(Operation)  A session s ∈ Session is a sequence of operations.
19 History ≜ SUBSET Session  A history h ∈ History is a set of sessions.
20 ----------
   Utilities.
24 Ops(h) ≜  Return the set of all operations in history h ∈ History.
25   UNION {Range(s) : s ∈ h}
26 ----------
   Well-formedness of history h ∈ History:
   − TODO: type invariants
   - uniqueness of oids
33 WellFormed(h) ≜
34   ∧ h ∈ History
35   ∧ Cardinality(Ops(h)) = ReduceSet(LAMBDA s, x : Len(s) + x, h, 0)
36 ----------
   Axioms used in the defintions of causal consistency
41 ProgramOrder(h) ≜  a union of total orders among operations in the same session
42     UNION {Seq2Rel(s) : s ∈ h}
43 POPast(h, o) ≜  the set of operations that preceed o ∈ Operation in program order in history h ∈ History
44     InverseImage(ProgramOrder(h), o)
45  CausalPast(h, co, o)
46 ----------
   Sequential semantics of read-write registers.
50 ----------
   Specification of Causal Consistency: CC, CCv, and CM
54 CCv(h) ≜  Check whether h ∈ History satisfies CCv (Causal Convergence)
55   ∧ WellFormed(h)
56   ∧ LET ops ≜ Ops(h)
57     IN   ∧ ∃ co ∈ SUBSET (ops × ops) :
58             ∃ arb ∈ SUBSET (ops × ops) :
59               ∧ IsStrictPartialOrder(co, ops)
60               ∧ IsStrictTotalOrder(arb, ops)
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61                  ∧ Respect(co, ProgramOrder(h))   AxCausal
62                  ∧ Respect(arb, co)               AxArb
63                  ∧ ∀ op ∈ ops : TRUE              TODO: AxCausalArb
64      ∧ FALSE
65 ╚═══════════════════════════════════════════════════════════════════
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* Modification *History*
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