

The Best Queue Specifications You Will Ever See today probably

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November 2025



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 - Concurrent specification
 - Doesn't track queue contents
 - HOCAP-style specification
 - Tracks queue contents with added complexity

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- Project was advised by Amin

Specifications for Queues

Informal Queue Specification

- Queues consists of **initialize**, **enqueue**, and **dequeue**
- **initialize** creates an **empty queue**: `[]`
- **enqueue** adds a value, v , to the **beginning of the queue** xs_v : $v :: xs_v$
- **dequeue** depends on whether queue is empty:
 - If **non-empty**, $xs_v \text{ ++ } [v]$, remove value v at **end of queue** and return **Some** v
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Nature of Specifications

- Specifications written in **Iris**, a **higher order CSL**
- Expressed in terms of **Hoare triples**: $\{P\} e \{v.\Phi v\}$
- Hoare triples prove **partial correctness** of programs, e
- In particular: **safety**

Sequential Specification

Definition (Sequential Specification)

$\exists \text{isQueues}_S : Val \rightarrow List\ Val \rightarrow SeqQgnames \rightarrow \text{Prop}.$

- The proposition $\text{isQueues}(v_q, xs_v, G)$, states that value v_q represents the queue, which contains elements xs_v
- $G \in SeqQgnames$ is a collection of ghost names (depends on specific queue)
- Specification consists of three Hoare triples – one for each queue function
- **Important:** isQueues not required to be persistent!

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$\wedge \forall v_q, xs_v, G. \{\text{isQueues}_S(v_q, xs_v, G)\}$

dequeue v_q

$\left\{ w. \begin{array}{l} (xs_v = [] * w = \text{None} * \text{isQueues}_S(v_q, xs_v, G)) \vee \\ (\exists v, xs'_v. xs_v = xs'_v ++ [v] * w = \text{Some } v * \text{isQueues}_S(v_q, xs'_v, G)) \end{array} \right\}$

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- To support concurrent clients, we shall require the queue predicate be persistent
- Tracking the contents of queue in the way that the sequential specification did doesn't work
- Threads will start disagreeing on contents of queue, as they have only local view of contents
- Give up on tracking contents for now
- Instead, promise that all elements satisfy client-defined predicate, Ψ

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$$\exists \text{isQueue}_C : (\text{Val} \rightarrow \text{Prop}) \rightarrow \text{Val} \rightarrow \text{ConcQgnames} \rightarrow \text{Prop}.$$
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HOCP-style Specification - Abstract State RA

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- Idea: have **two “views”** of the **abstract state** of the queue

Authoritative view

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Owned by queue

Fragmental view

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- Construction **ensures**:

- authoritative and fragmental views always **agree** on abstract state of queue
- views can only be **updated in unison**
- Implemented using the **resource algebra**: $AUTH((FRAC \times AG(List\ Val))^?)$
- The **desirables** are captured by the following **lemmas**

Lemmas on the Abstract State RA

$$\vdash \Rightarrow \exists \gamma. \gamma \Rightarrow_{\bullet} xs_v * \gamma \Rightarrow_{\circ} xs_v \quad (\text{Abstract State Alloc})$$

$$\gamma \Rightarrow_{\bullet} xs'_v * \gamma \Rightarrow_{\circ} xs_v \vdash xs_v = xs'_v \quad (\text{Abstract State Agree})$$

$$\gamma \Rightarrow_{\bullet} xs'_v * \gamma \Rightarrow_{\circ} xs_v \Rightarrow \gamma \Rightarrow_{\bullet} xs''_v * \gamma \Rightarrow_{\circ} xs_v \quad (\text{Abstract State Update})$$

HOCAP-style Specification

- Post-condition of `initialize` specification gives fragmental view to clients
- Hoare triples for `enqueue` and `dequeue` are conditioned on view-shifts
- Clients must show that they can supply the fragmental view, so that the abstract (and concrete) state can be updated
- View-shifts and Hoare-triples parametrised by predicates P and Q
 - Client might have resources that need to be updated as a result of `enqueue/dequeue`
 - P is the clients resources before `enqueue/dequeue` and Q the resources after

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Queue Client - A PoC Client

- Add two numbers after having two threads enqueue and subsequently dequeue them

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unwrap w  $\triangleq$  match w with None  $\Rightarrow$  () () | Some v  $\Rightarrow$  v end
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enqdeq vq c  $\triangleq$  enqueue vq c; unwrap(dequeue vq)
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queueAdd a b  $\triangleq$ 
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let vq = initialize () in  
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- **HOCAP-style** specification `supports consistency` and `tracks queue contents`, allowing us to `exclude cases` where `dequeue` returns `None`

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Queue Client - A PoC Client (continued)

Lemma (QueueAdd Specification)

$$\forall a, b \in \mathbb{Z}. \{ \text{True} \} \text{ queueAdd } a \ b \{ v.v = a + b \}$$

Queue Client - A PoC Client (continued)

Lemma (QueueAdd Specification)

$$\forall a, b \in \mathbb{Z}. \{ \text{True} \} \text{ queueAdd } a \ b \{ v.v = a + b \}$$

- Proof idea: create invariant capturing possible states of queue contents
- Tokens are used to reason about which state we are in

Definition (Invariant for QueueAdd)

$$\begin{aligned} I_{QA}(G, Ga, a, b) \triangleq & G.\gamma_{\text{Abst}} \Rightarrow_o [] * \text{TokD1 } Ga * \text{TokD2 } Ga \vee \\ & G.\gamma_{\text{Abst}} \Rightarrow_o [a] * \text{TokA } Ga * (\text{TokD1 } Ga \vee \text{TokD2 } Ga) \vee \\ & G.\gamma_{\text{Abst}} \Rightarrow_o [b] * \text{TokB } Ga * (\text{TokD1 } Ga \vee \text{TokD2 } Ga) \vee \\ & G.\gamma_{\text{Abst}} \Rightarrow_o [a; b] * \text{TokA } Ga * \text{TokB } Ga \vee \\ & G.\gamma_{\text{Abst}} \Rightarrow_o [b; a] * \text{TokB } Ga * \text{TokA } Ga \end{aligned}$$

- When using the HOCAP-style Queue specification to prove the above, we will make P and Q talk about the tokens.
- E.g for enqueue:
 - $P = \text{TokA } Ga \vee \text{TokB } Ga$
 - $Q = \text{TokD1 } Ga \vee \text{TokD2 } Ga$

Queue Specifications Overview

Spec\Feature	Supports Tracking	Supports Concurrency	
Sequential	✓	✗	
Concurrent	✗	✓	
HOCAP	✓	✓	

Queue Specifications Overview

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Concurrent	✗	✓	\$249
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- HOCAP generalises Sequential and Concurrent specs
- In fact, they are provably derivable from HOCAP

HOCP Derives Sequential

Definition (Sequential Specification (reminder))

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dequeue v_q

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- Choose $\text{isQueues}(v_q, xs_v, G) = \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$

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$\wedge \forall v_q, v, G, P, Q. \left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} G.\gamma_{\text{Abst}} \Rightarrow_\bullet (v :: xs_v) * Q \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ enqueue } v_q \vee \{ w.Q \}$

$\wedge \forall v_q, G, P, Q.$
$$\left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} \left(\begin{array}{l} (xs_v = [] * G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * Q(\text{None})) \\ \vee \left(\begin{array}{l} \exists v, xs'_v. xs_v = xs'_v ++ [v] * \\ G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs'_v * Q(\text{Some } v) \end{array} \right) \end{array} \right) \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ dequeue } v_q \{ w.Q(w) \}$$

- Choose $\text{isQueues}(v_q, xs_v, G) = \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
- Initialise then follows directly

HOCAP Derives Sequential

Definition (HOCAP Specification)

$\exists \text{isQueue} : Val \rightarrow Qgnames \rightarrow \text{Prop.}$

$\forall v_q, G. \text{isQueue}(v_q, G) \implies \square \text{isQueue}(v_q, G)$

$\wedge \{ \text{True} \} \text{ initialize } () \{ v_q. \exists G. \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o [] \}$

$\wedge \forall v_q, v, G, P, Q. \left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} G.\gamma_{\text{Abst}} \Rightarrow_\bullet (v :: xs_v) * Q \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ enqueue } v_q \vee \{ w.Q \}$

$\wedge \forall v_q, G, P, Q.$
$$\left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} \left(\begin{array}{l} (xs_v = [] * G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * Q(\text{None})) \\ \vee \left(\begin{array}{l} \exists v, xs'_v. xs_v = xs'_v ++ [v] * \\ G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs'_v * Q(\text{Some } v) \end{array} \right) \end{array} \right) \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ dequeue } v_q \{ w.Q(w) \}$$

- Choose $\text{isQueues}(v_q, xs_v, G) = \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
- Initialise then follows directly
- For enqueue, pick
 - $P = G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
 - $Q = G.\gamma_{\text{Abst}} \Rightarrow_o v :: xs_v$

HOCAP Derives Sequential

Definition (HOCAP Specification)

$\exists \text{isQueue} : Val \rightarrow Qgnames \rightarrow \text{Prop.}$

$\forall v_q, G. \text{isQueue}(v_q, G) \implies \square \text{isQueue}(v_q, G)$

$\wedge \{ \text{True} \} \text{ initialize } () \{ v_q. \exists G. \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o [] \}$

$\wedge \forall v_q, v, G, P, Q. \left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} G.\gamma_{\text{Abst}} \Rightarrow_\bullet (v :: xs_v) * Q \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ enqueue } v_q \vee \{ w.Q \}$

$\wedge \forall v_q, G, P, Q.$
$$\left(\forall xs_v. G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * P \Rightarrow_{\mathcal{E} \setminus \mathcal{N}, i \uparrow} \left(\begin{array}{l} (xs_v = [] * G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs_v * Q(\text{None})) \\ \vee \left(\begin{array}{l} \exists v, xs'_v. xs_v = xs'_v ++ [v] * \\ G.\gamma_{\text{Abst}} \Rightarrow_\bullet xs'_v * Q(\text{Some } v) \end{array} \right) \end{array} \right) \right) -* \{ \text{isQueue}(v_q, G) * P \} \text{ dequeue } v_q \{ w.Q(w) \}$$

- Choose $\text{isQueues}(v_q, xs_v, G) = \text{isQueue}(v_q, G) * G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
- Initialise then follows directly
- For enqueue, pick
 - $P = G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
 - $Q = G.\gamma_{\text{Abst}} \Rightarrow_o v :: xs_v$
- For dequeue, pick
 - $P = G.\gamma_{\text{Abst}} \Rightarrow_o xs_v$
 - $Q(w) = (G.\gamma_{\text{Abst}} \Rightarrow_o [] * w = \text{None}) \vee (\exists v, xs'_v. xs_v = xs'_v ++ [v] * w = \text{Some } v * G.\gamma_{\text{Abst}} \Rightarrow_o xs'_v)$

HOCP Derives Concurrent

Left as an exercise :)

Q.E.D

Thanks for your time

Questions?