Ray Internals

Complete Technical Guide

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A comprehensive technical deep-dive into Ray's distributed computing architecture, implementation details, and internal systems.

Chapter 1: Part I: Ray Fundamentals

# Chapter 1: Ray Architecture Overview

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## Introduction

Ray is a distributed computing framework designed for machine learning and AI workloads. This chapter provides a comprehensive overview of Ray's architecture, covering the fundamental components, their interactions, and the overall system design that enables scalable distributed computing.

### What is Ray?

Ray is an open-source unified framework for scaling AI workloads. It provides:

* \*\*Distributed Computing\*\*: Scale Python workloads across multiple machines
* \*\*Unified API\*\*: Single interface for tasks, actors, and data processing
* \*\*Fault Tolerance\*\*: Built-in error handling and recovery mechanisms
* \*\*Resource Management\*\*: Efficient allocation of CPU, GPU, and memory resources
* \*\*Ecosystem\*\*: Libraries for ML (Ray Train), reinforcement learning (Ray RLlib), hyperparameter tuning (Ray Tune), and more

### Key Features

* \*\*Multi-level Scheduling\*\*: Task-level, actor-level, and placement group scheduling
* \*\*Resource-Aware\*\*: CPU, GPU, memory, and custom resource scheduling
* \*\*Placement Strategies\*\*: PACK, SPREAD, STRICT\_PACK, STRICT\_SPREAD
* \*\*Locality Optimization\*\*: Data locality-aware task placement
* \*\*Dynamic Scaling\*\*: Integration with autoscaler for cluster growth/shrinkage
* \*\*Label-Based Scheduling\*\*: Node affinity and label constraints
* \*\*Performance Optimization\*\*: Efficient algorithms for large-scale clusters

### Scheduling Hierarchy

graph TD  
 A[User Workload] --> B[Core Worker]  
 B --> C[Lease Policy]  
 C --> D[Raylet Node Manager]  
 D --> E[Cluster Task Manager]  
 E --> F[Cluster Resource Scheduler]  
 F --> G[Scheduling Policies]  
 G --> H[Local Task Manager]  
 H --> I[Worker Pool]  
   
 J[GCS Server] --> K[GCS Actor Scheduler]  
 J --> L[GCS Placement Group Scheduler]  
   
 K --> F  
 L --> F  
   
 M[Autoscaler] --> N[Resource Demand Scheduler]  
 N --> O[Node Provider]

## Scheduling Architecture Overview

### Multi-Level Scheduling Architecture

Ray implements a hierarchical scheduling architecture with multiple decision points:

#### 1. Client-Side Scheduling

graph LR  
 A[ray.remote Call] --> B[Core Worker]  
 B --> C[Locality-Aware Lease Policy]  
 C --> D[Best Node Selection]  
 D --> E[Raylet RPC]

Location: src/ray/core\_worker/lease\_policy.cc

The client-side scheduling makes initial placement decisions based on:

* Data locality (object location)
* Scheduling strategies (spread, node affinity)
* Resource requirements

#### 2. Raylet-Level Scheduling

graph TD  
 A[Raylet Receives Task] --> B[Cluster Task Manager]  
 B --> C[Resource Availability Check]  
 C --> D{Resources Available?}  
 D -->|Yes| E[Local Task Manager]  
 D -->|No| F[Spillback Decision]  
 F --> G[Remote Node Selection]  
 G --> H[Forward to Remote Raylet]  
 E --> I[Worker Assignment]

Location: src/ray/raylet/scheduling/cluster\_task\_manager.cc

#### 3. GCS-Level Scheduling

graph TD  
 A[GCS Scheduling Request] --> B{Task Type}  
 B -->|Actor Creation| C[GCS Actor Scheduler]  
 B -->|Placement Group| D[GCS Placement Group Scheduler]  
 C --> E[Cluster Resource Scheduler]  
 D --> E  
 E --> F[Node Selection]  
 F --> G[Resource Reservation]

Location: src/ray/gcs/gcs\_server/gcs\_actor\_scheduler.cc

### Core Scheduling Flow

sequenceDiagram  
 participant CW as Core Worker  
 participant LP as Lease Policy  
 participant RM as Raylet Manager  
 participant CTM as Cluster Task Manager  
 participant CRS as Cluster Resource Scheduler  
 participant LTM as Local Task Manager  
 participant WP as Worker Pool  
  
 CW->>LP: GetBestNodeForTask()  
 LP->>LP: Analyze locality & strategy  
 LP->>RM: RequestWorkerLease()  
 RM->>CTM: QueueAndScheduleTask()  
 CTM->>CRS: GetBestSchedulableNode()  
 CRS->>CRS: Apply scheduling policy  
 CRS-->>CTM: Selected node  
 CTM->>LTM: QueueAndScheduleTask() [if local]  
 LTM->>WP: PopWorker()  
 WP-->>LTM: Worker instance  
 LTM-->>CTM: Task dispatched

## Core Scheduling Components

### ClusterResourceScheduler

Location: src/ray/raylet/scheduling/cluster\_resource\_scheduler.h

The central coordinator for cluster-wide resource scheduling decisions.

class ClusterResourceScheduler {  
 // Core scheduling method  
 scheduling::NodeID GetBestSchedulableNode(  
 const ResourceRequest &resource\_request,  
 const rpc::SchedulingStrategy &scheduling\_strategy,  
 bool actor\_creation,  
 bool force\_spillback,  
 const std::string &preferred\_node\_id,  
 int64\_t \*total\_violations,  
 bool \*is\_infeasible);  
   
 // Bundle scheduling for placement groups  
 SchedulingResult Schedule(  
 const std::vector<const ResourceRequest \*> &resource\_request\_list,  
 SchedulingOptions options);  
}

Key Responsibilities:

* Node feasibility checking
* Resource availability tracking
* Scheduling strategy implementation
* Placement group bundle scheduling

### ClusterTaskManager

Location: src/ray/raylet/scheduling/cluster\_task\_manager.h

Manages task queuing and scheduling at the cluster level.

class ClusterTaskManager {  
 void QueueAndScheduleTask(  
 RayTask task,  
 bool grant\_or\_reject,  
 bool is\_selected\_based\_on\_locality,  
 rpc::RequestWorkerLeaseReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback);  
   
 void ScheduleAndDispatchTasks();  
}

Scheduling Queues:

* `tasks\_to\_schedule\_`: Tasks waiting for resources
* `infeasible\_tasks\_`: Tasks that cannot be scheduled

### LocalTaskManager

Location: src/ray/raylet/local\_task\_manager.h

Handles local task execution and worker management.

class LocalTaskManager {  
 void QueueAndScheduleTask(std::shared\_ptr<internal::Work> work);  
 void ScheduleAndDispatchTasks();  
 bool TrySpillback(const std::shared\_ptr<internal::Work> &work,  
 bool &is\_infeasible);  
}

Fairness Policy: Implements CPU-fair scheduling to prevent resource starvation:

// From src/ray/raylet/local\_task\_manager.cc  
if (total\_cpu\_requests\_ > total\_cpus) {  
 RAY\_LOG(DEBUG) << "Applying fairness policy. Total CPU requests ("  
 << total\_cpu\_requests\_ << ") exceed total CPUs ("   
 << total\_cpus << ")";  
 // Apply fair dispatching logic  
}

### Scheduling Policies

Location: src/ray/raylet/scheduling/policy/

Ray implements multiple scheduling policies:

#### HybridSchedulingPolicy

* Default scheduling strategy
* Balances locality and load distribution
* Configurable spread threshold

#### SpreadSchedulingPolicy

* Distributes tasks across nodes
* Minimizes resource contention
* Used for embarrassingly parallel workloads

#### NodeAffinitySchedulingPolicy

* Hard/soft node constraints
* Supports spillback on unavailability
* Critical for stateful workloads

#### NodeLabelSchedulingPolicy

class NodeLabelSchedulingPolicy : public ISchedulingPolicy {  
 scheduling::NodeID Schedule(const ResourceRequest &resource\_request,  
 SchedulingOptions options) override;  
private:  
 bool IsNodeMatchLabelExpression(const Node &node,  
 const rpc::LabelMatchExpression &expression);  
};

### Scheduling Context and Options

Location: src/ray/raylet/scheduling/policy/scheduling\_options.h

struct SchedulingOptions {  
 SchedulingType scheduling\_type;  
 float spread\_threshold;  
 bool avoid\_local\_node;  
 bool require\_node\_available;  
 bool avoid\_gpu\_nodes;  
 double max\_cpu\_fraction\_per\_node; // For placement groups  
   
 static SchedulingOptions Hybrid(bool avoid\_local\_node,  
 bool require\_node\_available,  
 const std::string &preferred\_node\_id);  
   
 static SchedulingOptions BundlePack(double max\_cpu\_fraction\_per\_node = 1.0);  
 static SchedulingOptions BundleStrictSpread(double max\_cpu\_fraction\_per\_node = 1.0);  
};

## Resource Management and Allocation

### Resource Model

Ray uses a multi-dimensional resource model:

// Resource types from src/ray/common/scheduling/scheduling\_ids.h  
enum PredefinedResources {  
 CPU = 0,  
 MEM = 1,  
 GPU = 2,  
 OBJECT\_STORE\_MEM = 3,  
 // Custom resources start from 4  
};

### Resource Request Structure

class ResourceRequest {  
 ResourceSet resource\_set\_; // Required resources  
 LabelSelector label\_selector\_; // Node label requirements  
 bool requires\_object\_store\_memory\_; // Memory constraint flag  
   
 bool IsEmpty() const;  
 const ResourceSet &GetResourceSet() const;  
 bool RequiresObjectStoreMemory() const;  
};

### NodeResources

Location: src/ray/common/scheduling/cluster\_resource\_data.h

struct NodeResources {  
 NodeResourceSet total; // Total node capacity  
 NodeResourceSet available; // Currently available  
 NodeResourceSet normal\_task\_resources; // Reserved for tasks  
 absl::flat\_hash\_map<std::string, std::string> labels; // Node labels  
 bool object\_pulls\_queued; // Object store status  
   
 bool IsAvailable(const ResourceRequest &resource\_request) const;  
 bool IsFeasible(const ResourceRequest &resource\_request) const;  
 bool HasRequiredLabels(const LabelSelector &label\_selector) const;  
 float CalculateCriticalResourceUtilization() const;  
};

### Resource Allocation Algorithm

bool ClusterResourceScheduler::IsSchedulable(  
 const ResourceRequest &resource\_request,  
 scheduling::NodeID node\_id) const {  
   
 return cluster\_resource\_manager\_->HasAvailableResources(  
 node\_id,  
 resource\_request,  
 /\*ignore\_object\_store\_memory\_requirement\*/   
 node\_id == local\_node\_id\_) &&  
 NodeAvailable(node\_id);  
}

### Dynamic Resource Management

// From src/ray/raylet/scheduling/cluster\_resource\_scheduler\_test.cc  
TEST\_F(ClusterResourceSchedulerTest, DynamicResourceTest) {  
 // Add dynamic resources at runtime  
 resource\_scheduler.GetLocalResourceManager().AddLocalResourceInstances(  
 scheduling::ResourceID("custom123"), {0., 1.0, 1.0});  
   
 // Verify schedulability  
 auto result = resource\_scheduler.GetBestSchedulableNode(resource\_request, ...);  
 ASSERT\_FALSE(result.IsNil());  
}

### Resource Binpacking

Ray implements sophisticated binpacking for resource allocation:

graph TD  
 A[Resource Request] --> B[Sort by Resource Requirements]  
 B --> C[Find Best Fit Node]  
 C --> D{Resources Available?}  
 D -->|Yes| E[Allocate Resources]  
 D -->|No| F[Try Next Node]  
 F --> G{More Nodes?}  
 G -->|Yes| C  
 G -->|No| H[Request Infeasible]  
 E --> I[Update Node Resources]

## Task Scheduling Algorithms

### Hybrid Scheduling Algorithm

Default Strategy: Balances locality and load distribution

// Configuration from src/ray/raylet/scheduling/cluster\_resource\_scheduler.cc  
best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::Hybrid(  
 /\*avoid\_local\_node\*/ force\_spillback,  
 /\*require\_node\_available\*/ force\_spillback,  
 preferred\_node\_id));

Algorithm Steps: 1. Score Calculation: Based on resource utilization 2. Top-K Selection: Choose from best k nodes (default: 20% of cluster) 3. Random Selection: Within top-k for load balancing

Scoring Function:

float NodeResources::CalculateCriticalResourceUtilization() const {  
 float highest = 0;  
 for (const auto &i : {CPU, MEM, OBJECT\_STORE\_MEM}) {  
 float utilization = 1 - (available / total);  
 if (utilization > highest) {  
 highest = utilization;  
 }  
 }  
 return highest;  
}

### Spread Scheduling Algorithm

Purpose: Distribute tasks across maximum number of nodes

// From scheduling policy tests  
TEST\_F(SchedulingPolicyTest, SpreadSchedulingStrategyTest) {  
 rpc::SchedulingStrategy scheduling\_strategy;  
 scheduling\_strategy.mutable\_spread\_scheduling\_strategy();  
   
 auto node\_id = resource\_scheduler.GetBestSchedulableNode(  
 resource\_request, LabelSelector(), scheduling\_strategy, ...);  
}

Implementation:

* Prioritizes nodes with lowest task count
* Avoids resource hotspots
* Maximizes fault tolerance

### Node Affinity Scheduling

Hard Affinity: Must run on specific node

if (IsHardNodeAffinitySchedulingStrategy(scheduling\_strategy)) {  
 // Must schedule on specified node or fail  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::NodeAffinity(  
 force\_spillback, force\_spillback,  
 scheduling\_strategy.node\_affinity\_scheduling\_strategy().node\_id(),  
 /\*soft=\*/false, /\*spill\_on\_unavailable=\*/false,  
 /\*fail\_on\_unavailable=\*/true));  
}

Soft Affinity: Prefer specific node but allow spillback

scheduling\_strategy.mutable\_node\_affinity\_scheduling\_strategy()->set\_soft(true);  
// Will try preferred node first, then other nodes

### Fair Scheduling

CPU Fair Scheduling: Prevents starvation across scheduling classes

// From src/ray/raylet/local\_task\_manager.cc  
if (total\_cpu\_requests\_ > total\_cpus) {  
 // Calculate fair share per scheduling class  
 double fair\_share = total\_cpus / num\_classes\_with\_cpu;  
   
 // Apply throttling based on fair share  
 for (auto &[scheduling\_class, dispatch\_queue] : tasks\_to\_dispatch\_) {  
 double cpu\_request = /\* CPU required by this class \*/;  
 if (cpu\_request > fair\_share) {  
 // Throttle this class  
 next\_update\_time = current\_time + throttle\_delay;  
 }  
 }  
}

## Actor Placement and Scheduling

### Actor Scheduling Architecture

Location: src/ray/gcs/gcs\_server/gcs\_actor\_scheduler.cc

Ray provides two actor scheduling modes:

#### 1. GCS-Based Actor Scheduling

void GcsActorScheduler::ScheduleByGcs(std::shared\_ptr<GcsActor> actor) {  
 // Create task for actor creation  
 auto task = std::make\_shared<RayTask>(actor->GetCreationTaskSpecification());  
   
 // Use cluster task manager for scheduling  
 cluster\_task\_manager\_.QueueAndScheduleTask(  
 std::move(task),  
 /\*grant\_or\_reject\*/ false,  
 /\*is\_selected\_based\_on\_locality\*/ false,  
 reply.get(),  
 send\_reply\_callback);  
}

#### 2. Raylet-Based Actor Scheduling

void GcsActorScheduler::ScheduleByRaylet(std::shared\_ptr<GcsActor> actor) {  
 // Select forwarding node  
 auto node\_id = SelectForwardingNode(actor);  
   
 // Lease worker directly from node  
 LeaseWorkerFromNode(actor, node.value());  
}

### Actor Resource Requirements

Placement vs Execution Resources:

// From src/ray/common/task/task\_spec.cc  
const auto &resource\_set =   
 (is\_actor\_creation\_task && should\_report\_placement\_resources)  
 ? GetRequiredPlacementResources() // For scheduling decisions  
 : GetRequiredResources(); // For execution

Actor Creation Example:

@ray.remote(num\_cpus=2, num\_gpus=1, memory=1000)  
class MyActor:  
 def \_\_init\_\_(self):  
 pass  
   
 def method(self):  
 pass  
  
# Actor placement considers both creation and method resources  
actor = MyActor.remote()

### Actor Lifecycle and Scheduling

graph TD  
 A[Actor Creation Request] --> B[GCS Actor Scheduler]  
 B --> C{Scheduling Mode}  
 C -->|GCS Scheduling| D[Cluster Task Manager]  
 C -->|Raylet Scheduling| E[Select Forwarding Node]  
 D --> F[Resource Allocation]  
 E --> G[Direct Worker Lease]  
 F --> H[Worker Assignment]  
 G --> H  
 H --> I[Actor Initialization]  
 I --> J[Ready for Method Calls]

### Actor Scheduling Considerations

Resource Lifetime: Actors hold resources for their entire lifetime

if (task\_spec.IsActorCreationTask()) {  
 // The actor belongs to this worker now  
 worker->SetLifetimeAllocatedInstances(allocated\_instances);  
} else {  
 worker->SetAllocatedInstances(allocated\_instances);  
}

Scheduling Class: Actors use placement resources for scheduling decisions

TEST(TaskSpecTest, TestActorSchedulingClass) {  
 // Actor's scheduling class determined by placement resources  
 TaskSpecification actor\_task(actor\_task\_spec\_proto);  
 TaskSpecification regular\_task(regular\_task\_spec\_proto);  
   
 ASSERT\_EQ(regular\_task.GetSchedulingClass(), actor\_task.GetSchedulingClass());  
}

## Placement Group Scheduling

### Placement Group Architecture

Location: src/ray/gcs/gcs\_server/gcs\_placement\_group\_scheduler.cc

Placement groups enable gang scheduling of related resources across multiple nodes.

class GcsPlacementGroupScheduler {  
 void SchedulePlacementGroup(  
 std::shared\_ptr<GcsPlacementGroup> placement\_group,  
 PGSchedulingFailureCallback failure\_callback,  
 PGSchedulingSuccessfulCallback success\_callback);  
}

### Bundle Specification

Location: src/ray/common/bundle\_spec.h

class BundleSpecification {  
 BundleID BundleId() const;  
 PlacementGroupID PlacementGroupId() const;  
 NodeID NodeId() const;  
 int64\_t Index() const;  
 const ResourceRequest &GetRequiredResources() const;  
 const absl::flat\_hash\_map<std::string, double> &GetFormattedResources() const;  
};

### Placement Strategies

#### PACK Strategy

case rpc::PlacementStrategy::PACK:  
 return SchedulingOptions::BundlePack(max\_cpu\_fraction\_per\_node);

* \*\*Goal\*\*: Minimize number of nodes used
* \*\*Use Case\*\*: Maximize locality, minimize network overhead
* \*\*Algorithm\*\*: First-fit decreasing binpacking

#### SPREAD Strategy

case rpc::PlacementStrategy::SPREAD:  
 return SchedulingOptions::BundleSpread(max\_cpu\_fraction\_per\_node);

* \*\*Goal\*\*: Distribute bundles across nodes
* \*\*Use Case\*\*: Fault tolerance, load distribution
* \*\*Algorithm\*\*: Round-robin placement with load balancing

#### STRICT\_PACK Strategy

case rpc::PlacementStrategy::STRICT\_PACK:  
 return SchedulingOptions::BundleStrictPack(  
 max\_cpu\_fraction\_per\_node,  
 soft\_target\_node\_id);

* \*\*Goal\*\*: All bundles on single node (if possible)
* \*\*Use Case\*\*: Shared memory, minimal latency
* \*\*Algorithm\*\*: Single-node placement with fallback

#### STRICT\_SPREAD Strategy

case rpc::PlacementStrategy::STRICT\_SPREAD:  
 return SchedulingOptions::BundleStrictSpread(  
 max\_cpu\_fraction\_per\_node,   
 CreateSchedulingContext(placement\_group\_id));

* \*\*Goal\*\*: Each bundle on different node
* \*\*Use Case\*\*: Maximum fault tolerance
* \*\*Algorithm\*\*: One bundle per node constraint

### Bundle Scheduling Algorithm

graph TD  
 A[Placement Group Request] --> B[Parse Bundles]  
 B --> C[Sort by Resource Requirements]  
 C --> D[Apply Placement Strategy]  
 D --> E{Strategy Type}  
 E -->|PACK| F[First-Fit Decreasing]  
 E -->|SPREAD| G[Round-Robin Distribution]  
 E -->|STRICT\_PACK| H[Single Node Placement]  
 E -->|STRICT\_SPREAD| I[One Bundle Per Node]  
 F --> J[Resource Reservation]  
 G --> J  
 H --> J  
 I --> J  
 J --> K[Bundle Commitment]

### Bundle Resource Formatting

Ray formats placement group resources with special naming:

// From src/ray/common/bundle\_spec.h  
std::string FormatPlacementGroupResource(  
 const std::string &original\_resource\_name,  
 const std::string &group\_id\_str,  
 int64\_t bundle\_index) {  
   
 if (bundle\_index == -1) {  
 // Wildcard resource: CPU\_group\_<group\_id>  
 return original\_resource\_name + "\_group\_" + group\_id\_str;  
 } else {  
 // Indexed resource: CPU\_group\_<bundle\_index>\_<group\_id>  
 return original\_resource\_name + "\_group\_" +   
 std::to\_string(bundle\_index) + "\_" + group\_id\_str;  
 }  
}

### CPU Fraction Limits

Purpose: Prevent placement groups from monopolizing nodes

bool AllocationWillExceedMaxCpuFraction(  
 const NodeResources &node\_resources,  
 const ResourceRequest &bundle\_resource\_request,  
 double max\_cpu\_fraction\_per\_node,  
 double available\_cpus\_before\_current\_pg\_request) {  
   
 if (max\_cpu\_fraction\_per\_node == 1.0) {  
 return false; // No limit  
 }  
   
 auto max\_reservable\_cpus =   
 max\_cpu\_fraction\_per\_node \* node\_resources.total.Get(cpu\_id).Double();  
   
 // Ensure at least 1 CPU is excluded from placement groups  
 if (max\_reservable\_cpus > total\_cpus - 1) {  
 max\_reservable\_cpus = total\_cpus - 1;  
 }  
   
 return cpus\_used\_by\_pg\_after > max\_reservable\_cpus;  
}

### Placement Group Lifecycle

sequenceDiagram  
 participant User  
 participant GCS as GCS PG Scheduler  
 participant CRS as Cluster Resource Scheduler  
 participant Raylet  
 participant Worker  
  
 User->>GCS: ray.util.placement\_group()  
 GCS->>GCS: Parse bundles & strategy  
 GCS->>CRS: Schedule(bundle\_list, options)  
 CRS->>CRS: Apply placement strategy  
 CRS-->>GCS: Selected nodes  
 GCS->>Raylet: PrepareBundleResources()  
 Raylet-->>GCS: Resources reserved  
 GCS->>Raylet: CommitBundleResources()  
 Raylet-->>GCS: Resources committed  
 GCS-->>User: Placement group ready  
   
 User->>Worker: Task with PG scheduling strategy  
 Worker->>Raylet: Use PG bundle resources

## Scheduling Strategies

### Strategy Types and Implementation

Ray supports multiple scheduling strategies through the rpc::SchedulingStrategy protocol buffer:

// From src/ray/raylet/scheduling/cluster\_resource\_scheduler.cc  
scheduling::NodeID ClusterResourceScheduler::GetBestSchedulableNode(  
 const ResourceRequest &resource\_request,  
 const rpc::SchedulingStrategy &scheduling\_strategy,  
 bool actor\_creation,  
 bool force\_spillback,  
 const std::string &preferred\_node\_id,  
 int64\_t \*total\_violations,  
 bool \*is\_infeasible) {  
   
 if (scheduling\_strategy.scheduling\_strategy\_case() ==  
 rpc::SchedulingStrategy::SchedulingStrategyCase::kSpreadSchedulingStrategy) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::Spread(force\_spillback, force\_spillback));  
   
 } else if (scheduling\_strategy.scheduling\_strategy\_case() ==  
 rpc::SchedulingStrategy::SchedulingStrategyCase::  
 kNodeAffinitySchedulingStrategy) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::NodeAffinity(/\* ... \*/));  
   
 } else if (scheduling\_strategy.has\_node\_label\_scheduling\_strategy()) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,   
 SchedulingOptions::NodeLabelScheduling(scheduling\_strategy));  
 }  
}

### DEFAULT Strategy

Implementation: Hybrid policy with configurable parameters

# Environment variables controlling DEFAULT strategy  
RAY\_scheduler\_spread\_threshold = 0.5 # Utilization threshold  
RAY\_scheduler\_top\_k\_fraction = 0.2 # Top-k selection ratio   
RAY\_scheduler\_top\_k\_absolute = 5 # Minimum top-k count

Algorithm: 1. Calculate node scores based on resource utilization 2. Select top-k nodes with lowest scores 3. Randomly choose from top-k for load balancing

### SPREAD Strategy

Purpose: Maximize distribution across nodes

import ray  
  
@ray.remote(scheduling\_strategy="SPREAD")  
def distributed\_task():  
 return "Running on different nodes"  
  
# Tasks will be distributed across available nodes  
futures = [distributed\_task.remote() for \_ in range(100)]

Implementation Details:

* Prioritizes nodes with fewer running tasks
* Considers resource utilization as secondary factor
* Useful for embarrassingly parallel workloads

### Node Affinity Strategy

Hard Affinity: Must run on specific node

import ray  
from ray.util.scheduling\_strategies import NodeAffinitySchedulingStrategy  
  
@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id="specific-node-id",   
 soft=False  
))  
def pinned\_task():  
 return "Must run on specific node"

Soft Affinity: Prefer specific node with fallback

@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id="preferred-node-id",   
 soft=True  
))  
def preferred\_task():  
 return "Prefers specific node but can run elsewhere"

### Placement Group Strategy

Bundle-Specific Scheduling:

import ray  
from ray.util.placement\_group import placement\_group  
from ray.util.scheduling\_strategies import PlacementGroupSchedulingStrategy  
  
# Create placement group  
pg = placement\_group([{"CPU": 2}, {"CPU": 2}], strategy="PACK")  
  
@ray.remote(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg,  
 placement\_group\_bundle\_index=0  
))  
def task\_on\_bundle\_0():  
 return "Running on bundle 0"  
  
@ray.remote(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg,  
 placement\_group\_bundle\_index=-1 # Any bundle  
))  
def task\_on\_any\_bundle():  
 return "Running on any available bundle"

## Node Affinity and Label-Based Scheduling

### Node Label Scheduling Policy

Location: src/ray/raylet/scheduling/policy/node\_label\_scheduling\_policy.cc

Ray supports sophisticated label-based scheduling for fine-grained node selection:

scheduling::NodeID NodeLabelSchedulingPolicy::Schedule(  
 const ResourceRequest &resource\_request,  
 SchedulingOptions options) {  
   
 // 1. Select feasible nodes  
 auto hard\_match\_nodes = SelectFeasibleNodes(resource\_request);  
   
 // 2. Filter by hard expressions  
 if (node\_label\_scheduling\_strategy.hard().expressions().size() > 0) {  
 hard\_match\_nodes = FilterNodesByLabelMatchExpressions(  
 hard\_match\_nodes, node\_label\_scheduling\_strategy.hard());  
 }  
   
 // 3. Filter by soft expressions   
 auto hard\_and\_soft\_match\_nodes = FilterNodesByLabelMatchExpressions(  
 hard\_match\_nodes, node\_label\_scheduling\_strategy.soft());  
   
 return SelectBestNode(hard\_match\_nodes, hard\_and\_soft\_match\_nodes, resource\_request);  
}

### Label Matching Implementation

bool NodeLabelSchedulingPolicy::IsNodeMatchLabelExpression(  
 const Node &node, const rpc::LabelMatchExpression &expression) const {  
   
 const auto &key = expression.key();  
 const auto &operator\_type = expression.operator\_();  
 const auto &values = expression.values();  
   
 switch (operator\_type) {  
 case rpc::LabelMatchExpression::IN:  
 return IsNodeLabelInValues(node, key, values);  
 case rpc::LabelMatchExpression::NOT\_IN:  
 return !IsNodeLabelInValues(node, key, values);  
 case rpc::LabelMatchExpression::EXISTS:  
 return IsNodeLabelKeyExists(node, key);  
 case rpc::LabelMatchExpression::DOES\_NOT\_EXIST:  
 return !IsNodeLabelKeyExists(node, key);  
 }  
}

### Label Selector Usage

import ray  
from ray.util.scheduling\_strategies import NodeLabelSchedulingStrategy  
  
# Hard constraints (must match)  
hard\_constraints = {  
 "ray.io/node-type": "gpu-node",  
 "zone": "us-west-1a"  
}  
  
# Soft constraints (preferred)  
soft\_constraints = {  
 "instance-type": "p3.2xlarge"  
}  
  
@ray.remote(scheduling\_strategy=NodeLabelSchedulingStrategy(  
 hard=hard\_constraints,  
 soft=soft\_constraints  
))  
def gpu\_task():  
 return "Running on GPU node in preferred zone"

### Node Label Management

Static Labels: Set during node startup

# Set node labels via environment  
export RAY\_NODE\_LABELS='{"zone":"us-west-1a","instance-type":"m5.large"}'  
ray start --head

Dynamic Labels: Updated at runtime

// From cluster resource data  
struct NodeResources {  
 absl::flat\_hash\_map<std::string, std::string> labels;  
   
 bool HasRequiredLabels(const LabelSelector &label\_selector) const;  
 bool NodeLabelMatchesConstraint(const LabelConstraint &constraint) const;  
};

## Locality-Aware Scheduling

### Locality-Aware Lease Policy

Location: src/ray/core\_worker/lease\_policy.cc

Ray implements data locality-aware scheduling to minimize data movement:

std::pair<rpc::Address, bool> LocalityAwareLeasePolicy::GetBestNodeForTask(  
 const TaskSpecification &spec) {  
   
 // Check for explicit scheduling strategies first  
 if (spec.IsSpreadSchedulingStrategy() || spec.IsNodeAffinitySchedulingStrategy()) {  
 return std::make\_pair(fallback\_rpc\_address\_, false);  
 }  
   
 // Pick node based on locality  
 if (auto node\_id = GetBestNodeIdForTask(spec)) {  
 if (auto addr = node\_addr\_factory\_(node\_id.value())) {  
 return std::make\_pair(addr.value(), true);  
 }  
 }  
   
 return std::make\_pair(fallback\_rpc\_address\_, false);  
}

### Locality Calculation

Criteria: Node with most object bytes local

std::optional<NodeID> LocalityAwareLeasePolicy::GetBestNodeIdForTask(  
 const TaskSpecification &spec) {  
   
 const auto &dependencies = spec.GetDependencies();  
 if (dependencies.empty()) {  
 return std::nullopt;  
 }  
   
 // Calculate locality scores for each node  
 absl::flat\_hash\_map<NodeID, int64\_t> locality\_scores;  
 for (const auto &obj\_id : dependencies) {  
 auto locality\_data = locality\_data\_provider\_.GetLocalityData(obj\_id);  
 for (const auto &node\_id : locality\_data.nodes\_containing\_object) {  
 locality\_scores[node\_id] += locality\_data.object\_size;  
 }  
 }  
   
 // Return node with highest locality score  
 return GetNodeWithMaxScore(locality\_scores);  
}

### Locality vs Strategy Priority

graph TD  
 A[Task Submission] --> B{Explicit Strategy?}  
 B -->|Yes| C[Use Explicit Strategy]  
 B -->|No| D[Check Data Locality]  
 D --> E{Objects Local?}  
 E -->|Yes| F[Select Node with Most Data]  
 E -->|No| G[Use Default Strategy]  
 C --> H[Schedule Task]  
 F --> H  
 G --> H

### Locality Testing

// From src/ray/tests/test\_scheduling.py  
def test\_locality\_aware\_leasing(ray\_start\_cluster):  
 @ray.remote(resources={"pin": 1})  
 def non\_local():  
 return ray.\_private.worker.global\_worker.node.unique\_id  
  
 @ray.remote  
 def f(x):  
 return ray.\_private.worker.global\_worker.node.unique\_id  
  
 # Test that task f() runs on the same node as non\_local()  
 # due to data locality  
 assert ray.get(f.remote(non\_local.remote())) == non\_local\_node.unique\_id

## Cluster Resource Scheduling

### Cluster Resource Manager

Location: src/ray/raylet/scheduling/cluster\_resource\_manager.h

Maintains global view of cluster resources:

class ClusterResourceManager {  
 // Add or update node resources  
 void AddOrUpdateNode(scheduling::NodeID node\_id,  
 const NodeResources &node\_resources);  
   
 // Check resource availability  
 bool HasAvailableResources(scheduling::NodeID node\_id,  
 const ResourceRequest &resource\_request) const;  
   
 // Resource allocation  
 bool SubtractNodeAvailableResources(scheduling::NodeID node\_id,  
 const ResourceRequest &resource\_request);  
};

### Resource Synchronization

sequenceDiagram  
 participant LRM as Local Resource Manager  
 participant CRM as Cluster Resource Manager  
 participant GCS as GCS Server  
 participant Remote as Remote Raylet  
  
 LRM->>CRM: UpdateLocalResources()  
 CRM->>GCS: ReportResourceUsage()  
 GCS->>Remote: BroadcastResourceUpdate()  
 Remote->>CRM: UpdateRemoteNodeResources()  
   
 Note over CRM: Maintains consistent cluster view

### Resource Reporting

Location: src/ray/raylet/scheduling/scheduler\_resource\_reporter.cc

void SchedulerResourceReporter::FillResourceUsage(rpc::ResourcesData &data) const {  
 // Report resource demands by shape  
 auto resource\_load\_by\_shape = data.mutable\_resource\_load\_by\_shape();  
   
 for (const auto &[scheduling\_class, task\_queue] : tasks\_to\_schedule\_) {  
 const auto &resources = scheduling\_class\_descriptor.resource\_set.GetResourceMap();  
 auto by\_shape\_entry = resource\_load\_by\_shape->Add();  
   
 for (const auto &resource : resources) {  
 (\*by\_shape\_entry->mutable\_shape())[resource.first] = resource.second;  
 }  
   
 by\_shape\_entry->set\_num\_ready\_requests\_queued(task\_queue.size());  
 }  
}

## Autoscaler Integration

### Resource Demand Scheduler

Location: python/ray/autoscaler/v2/scheduler.py

The autoscaler uses sophisticated scheduling algorithms to determine cluster scaling decisions:

class ResourceDemandScheduler(IResourceScheduler):  
 def schedule(self, request: SchedulingRequest) -> SchedulingReply:  
 ctx = self.ScheduleContext.from\_schedule\_request(request)  
   
 # 1. Enforce min workers per type  
 self.\_enforce\_min\_workers\_per\_type(ctx)  
   
 # 2. Enforce resource constraints  
 infeasible\_constraints = self.\_enforce\_resource\_constraints(  
 ctx, request.cluster\_resource\_constraints)  
   
 # 3. Schedule gang resource requests  
 infeasible\_gang\_requests = self.\_sched\_gang\_resource\_requests(  
 ctx, request.gang\_resource\_requests)  
   
 # 4. Schedule regular resource requests  
 infeasible\_requests = self.\_sched\_resource\_requests(  
 ctx, ResourceRequestUtil.ungroup\_by\_count(request.resource\_requests))  
   
 # 5. Enforce idle termination  
 self.\_enforce\_idle\_termination(ctx)  
   
 return SchedulingReply(  
 to\_launch=ctx.get\_launch\_requests(),  
 to\_terminate=ctx.get\_terminate\_requests(),  
 infeasible\_resource\_requests=infeasible\_requests,  
 infeasible\_gang\_resource\_requests=infeasible\_gang\_requests,  
 infeasible\_cluster\_resource\_constraints=infeasible\_constraints  
 )

### Binpacking Algorithm

def \_try\_schedule(  
 ctx: ScheduleContext,  
 requests\_to\_sched: List[ResourceRequest],  
 resource\_request\_source: ResourceRequestSource,  
) -> Tuple[List[SchedulingNode], List[ResourceRequest]]:  
   
 # Sort requests by complexity for better binpacking  
 def \_sort\_resource\_request(req: ResourceRequest) -> Tuple:  
 return (  
 len(req.placement\_constraints),  
 len(req.resources\_bundle.values()),  
 sum(req.resources\_bundle.values()),  
 sorted(req.resources\_bundle.items()),  
 )  
   
 requests\_to\_sched = sorted(  
 requests\_to\_sched, key=\_sort\_resource\_request, reverse=True)  
   
 # Try scheduling on existing nodes first  
 while len(requests\_to\_sched) > 0 and len(existing\_nodes) > 0:  
 best\_node, requests\_to\_sched, existing\_nodes = \  
 self.\_sched\_best\_node(requests\_to\_sched, existing\_nodes, resource\_request\_source)  
 if best\_node is None:  
 break  
 target\_nodes.append(best\_node)  
   
 # Try scheduling on new nodes  
 for node\_type, num\_available in node\_type\_available.items():  
 if num\_available > 0:  
 new\_node = SchedulingNode.from\_node\_config(  
 ctx.get\_node\_type\_configs()[node\_type],  
 status=SchedulingNodeStatus.TO\_LAUNCH)  
 # Try to schedule remaining requests on new node

### Placement Group Autoscaling

def placement\_groups\_to\_resource\_demands(  
 pending\_placement\_groups: List[PlacementGroupTableData],  
) -> Tuple[List[ResourceDict], List[List[ResourceDict]]]:  
   
 resource\_demand\_vector = []  
 unconverted = []  
   
 for placement\_group in pending\_placement\_groups:  
 shapes = [dict(bundle.unit\_resources) for bundle in placement\_group.bundles   
 if bundle.node\_id == b""] # Only unplaced bundles  
   
 if placement\_group.strategy == PlacementStrategy.PACK:  
 resource\_demand\_vector.extend(shapes)  
 elif placement\_group.strategy == PlacementStrategy.STRICT\_PACK:  
 # Combine all bundles into single demand  
 combined = collections.defaultdict(float)  
 for shape in shapes:  
 for label, quantity in shape.items():  
 combined[label] += quantity  
 resource\_demand\_vector.append(combined)  
 elif placement\_group.strategy == PlacementStrategy.STRICT\_SPREAD:  
 # Cannot be converted - needs special handling  
 unconverted.append(shapes)  
   
 return resource\_demand\_vector, unconverted

### Autoscaler Configuration

# Example autoscaler configuration  
cluster\_name: ray-cluster  
max\_workers: 100  
upscaling\_speed: 1.0  
idle\_timeout\_minutes: 5  
  
available\_node\_types:  
 ray.head.default:  
 min\_workers: 0  
 max\_workers: 0  
 resources: {"CPU": 4}  
   
 ray.worker.cpu:  
 min\_workers: 0  
 max\_workers: 50  
 resources: {"CPU": 8, "memory": 32000000000}  
   
 ray.worker.gpu:  
 min\_workers: 0  
 max\_workers: 10  
 resources: {"CPU": 16, "GPU": 4, "memory": 64000000000}

## Performance Characteristics

### Scheduling Latency

Typical Latencies:

* Local scheduling: 1-5ms
* Remote scheduling: 10-50ms
* Placement group creation: 100-1000ms
* Autoscaler response: 30-300s

### Scalability Metrics

Cluster Size: Ray scheduling tested up to 1000+ nodes

Task Throughput:

* Simple tasks: 100K+ tasks/second
* Complex scheduling: 10K+ tasks/second
* Placement groups: 100+ groups/second

### Memory Usage

Scheduler Memory Overhead:

// Per-node overhead in ClusterResourceManager  
struct NodeResources {  
 NodeResourceSet total; // ~1KB per node  
 NodeResourceSet available; // ~1KB per node   
 NodeResourceSet normal\_task\_resources; // ~1KB per node  
 absl::flat\_hash\_map<std::string, std::string> labels; // Variable  
};  
  
// Total: ~3KB + labels per node

Task Queue Memory:

// Per-task overhead in scheduling queues  
class Work {  
 RayTask task; // ~2KB per task  
 TaskResourceInstances allocated; // ~500B per task  
 WorkStatus state; // ~100B per task  
};  
  
// Total: ~2.6KB per queued task

### Performance Optimization

Top-K Selection: Reduces scheduling complexity from O(N) to O(K)

// Default configuration  
RAY\_scheduler\_top\_k\_fraction = 0.2 // 20% of nodes  
RAY\_scheduler\_top\_k\_absolute = 5 // Minimum 5 nodes

Caching: Resource views cached to avoid repeated calculations

class ClusterResourceManager {  
 // Cached resource calculations  
 mutable absl::flat\_hash\_map<scheduling::NodeID, float> utilization\_cache\_;  
 mutable int64\_t cache\_timestamp\_;  
};

## Configuration and Tuning

### Environment Variables

Core Scheduling:

# Spread threshold for hybrid scheduling  
export RAY\_scheduler\_spread\_threshold=0.5  
  
# Top-k node selection  
export RAY\_scheduler\_top\_k\_fraction=0.2  
export RAY\_scheduler\_top\_k\_absolute=5  
  
# Worker management  
export RAY\_num\_workers\_soft\_limit=1000  
export RAY\_maximum\_startup\_concurrency=10

Resource Management:

# Object store memory scheduling  
export RAY\_object\_store\_memory=1000000000  
  
# Pull manager configuration   
export RAY\_object\_manager\_pull\_timeout\_ms=10000  
export RAY\_object\_manager\_max\_bytes\_in\_flight=100000000

Placement Groups:

# CPU fraction limits  
export RAY\_placement\_group\_max\_cpu\_fraction\_per\_node=0.8  
  
# Bundle scheduling timeout  
export RAY\_placement\_group\_bundle\_resource\_timeout\_s=30

### Runtime Configuration

Cluster Resource Constraints:

import ray  
  
# Set cluster-wide resource constraints  
ray.autoscaler.sdk.request\_resources([  
 {"CPU": 100, "GPU": 10}, # Ensure cluster can handle this workload  
 {"memory": 1000000000} # Minimum memory requirement  
])

Node Type Configuration:

# Configure node types for autoscaling  
node\_config = {  
 "ray.worker.cpu": {  
 "min\_workers": 2,  
 "max\_workers": 20,  
 "resources": {"CPU": 8, "memory": 32000000000}  
 },  
 "ray.worker.gpu": {  
 "min\_workers": 0,   
 "max\_workers": 5,  
 "resources": {"CPU": 16, "GPU": 4, "memory": 64000000000}  
 }  
}

### Performance Tuning

For High Throughput:

# Increase worker limits  
export RAY\_num\_workers\_soft\_limit=2000  
export RAY\_maximum\_startup\_concurrency=50  
  
# Reduce scheduling overhead  
export RAY\_scheduler\_top\_k\_absolute=10  
export RAY\_scheduler\_spread\_threshold=0.3

For Low Latency:

# Prioritize local scheduling  
export RAY\_scheduler\_spread\_threshold=0.8  
export RAY\_scheduler\_top\_k\_fraction=0.1  
  
# Reduce worker startup time  
export RAY\_worker\_lease\_timeout\_milliseconds=1000

For Large Clusters:

# Optimize for scale  
export RAY\_scheduler\_top\_k\_fraction=0.1 # Top 10% of nodes  
export RAY\_raylet\_report\_resources\_period\_milliseconds=1000  
export RAY\_gcs\_resource\_report\_poll\_period\_milliseconds=1000

## Best Practices

### Task Scheduling

1. Use Appropriate Scheduling Strategies:

# For embarrassingly parallel workloads  
@ray.remote(scheduling\_strategy="SPREAD")  
def parallel\_task(data):  
 return process(data)  
  
# For data-dependent tasks (default locality-aware)  
@ray.remote  
def dependent\_task(large\_object):  
 return analyze(large\_object)  
  
# For specific hardware requirements  
@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id=gpu\_node\_id, soft=True))  
def gpu\_task():  
 return train\_model()

2. Resource Specification:

# Be specific about resource requirements  
@ray.remote(num\_cpus=2, num\_gpus=1, memory=4000\*1024\*1024)  
def resource\_intensive\_task():  
 return compute()  
  
# Use custom resources for specialized hardware  
@ray.remote(resources={"accelerator": 1})  
def accelerated\_task():  
 return specialized\_compute()

### Actor Placement

1. Consider Resource Lifetime:

# Actors hold resources for their lifetime  
@ray.remote(num\_cpus=4, num\_gpus=1)  
class ModelServer:  
 def \_\_init\_\_(self):  
 self.model = load\_large\_model()  
   
 def predict(self, data):  
 return self.model.predict(data)  
  
# Create fewer, long-lived actors rather than many short-lived ones  
server = ModelServer.remote()

2. Use Placement Groups for Related Actors:

# Group related actors together  
pg = placement\_group([{"CPU": 4}, {"CPU": 4}, {"CPU": 4}], strategy="PACK")  
  
actors = [  
 Actor.options(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg, placement\_group\_bundle\_index=i  
 )).remote() for i in range(3)  
]

### Placement Group Design

1. Choose Appropriate Strategies:

# For tightly coupled workloads  
pg\_pack = placement\_group([{"CPU": 2, "GPU": 1}] \* 4, strategy="PACK")  
  
# For fault tolerance  
pg\_spread = placement\_group([{"CPU": 2}] \* 8, strategy="SPREAD")  
  
# For strict requirements  
pg\_strict = placement\_group([{"CPU": 4}] \* 2, strategy="STRICT\_SPREAD")

2. Bundle Size Optimization:

# Avoid bundles larger than single node capacity  
# Bad: Bundle requires more than any node has  
bad\_pg = placement\_group([{"CPU": 64, "GPU": 8}]) # If max node has 32 CPU  
  
# Good: Bundle fits on available nodes  
good\_pg = placement\_group([{"CPU": 16, "GPU": 2}] \* 4)

### Autoscaler Optimization

1. Configure Appropriate Limits:

# Set realistic min/max workers  
available\_node\_types:  
 ray.worker.default:  
 min\_workers: 2 # Always keep some capacity  
 max\_workers: 100 # Prevent runaway scaling  
 upscaling\_speed: 2.0 # Scale up aggressively

2. Use Resource Constraints:

# Ensure cluster can handle expected workload  
ray.autoscaler.sdk.request\_resources([  
 {"CPU": 200, "memory": 500000000000}, # Expected peak usage  
])

## Troubleshooting

### Common Scheduling Issues

1. Tasks Stuck in Pending State:

Symptoms: Tasks remain in PENDING\_SCHEDULING state Causes:

* Insufficient cluster resources
* Infeasible resource requirements
* Node affinity to unavailable nodes

Debugging:

# Check cluster resources  
print(ray.cluster\_resources())  
print(ray.available\_resources())  
  
# Check task resource requirements  
@ray.remote(num\_cpus=1)  
def debug\_task():  
 return ray.get\_runtime\_context().get\_assigned\_resources()  
  
# Check for infeasible tasks  
ray.autoscaler.sdk.request\_resources([{"CPU": 1000}]) # Will show if infeasible

2. Poor Load Balancing:

Symptoms: Some nodes overloaded while others idle Causes:

* Inappropriate scheduling strategy
* Data locality overriding load balancing
* Sticky worker assignment

Solutions:

# Use SPREAD strategy for better distribution  
@ray.remote(scheduling\_strategy="SPREAD")  
def distributed\_task():  
 return compute()  
  
# Adjust spread threshold  
import os  
os.environ["RAY\_scheduler\_spread\_threshold"] = "0.3"

3. Placement Group Creation Failures:

Symptoms: Placement groups fail to create or timeout Causes:

* Insufficient cluster capacity
* Conflicting resource constraints
* Network partitions

Debugging:

import ray  
from ray.util.placement\_group import placement\_group  
  
# Check placement group status  
pg = placement\_group([{"CPU": 2}] \* 4, strategy="STRICT\_SPREAD")  
print(pg.ready()) # False if creation failed  
  
# Check bundle placement  
print(ray.util.placement\_group\_table())

### Performance Issues

1. High Scheduling Latency:

Symptoms: Long delays between task submission and execution Causes:

* Large cluster with inefficient node selection
* Complex placement constraints
* Resource fragmentation

Solutions:

# Reduce top-k selection size  
export RAY\_scheduler\_top\_k\_fraction=0.1  
  
# Increase spread threshold for faster local scheduling  
export RAY\_scheduler\_spread\_threshold=0.7

2. Memory Issues in Scheduler:

Symptoms: Raylet OOM, high memory usage in scheduling components Causes:

* Large number of queued tasks
* Memory leaks in scheduling data structures
* Excessive resource tracking overhead

Solutions:

# Limit concurrent tasks  
export RAY\_num\_workers\_soft\_limit=500  
  
# Reduce resource reporting frequency  
export RAY\_raylet\_report\_resources\_period\_milliseconds=5000

### Debugging Tools

1. Ray Status Commands:

# Check cluster state  
ray status  
  
# Check resource usage  
ray status --verbose  
  
# Check placement groups  
ray status --placement-groups

2. Programmatic Debugging:

# Check scheduling state  
import ray.\_private.state as state  
  
# Get pending tasks  
pending\_tasks = state.tasks(filters=[("state", "=", "PENDING\_SCHEDULING")])  
  
# Get resource usage by node  
nodes = state.nodes()  
for node in nodes:  
 print(f"Node {node['node\_id']}: {node['resources\_total']}")

3. Logging Configuration:

# Enable debug logging for scheduling  
export RAY\_LOG\_LEVEL=DEBUG  
export RAY\_BACKEND\_LOG\_LEVEL=DEBUG  
  
# Focus on specific components  
export RAY\_LOG\_TO\_STDERR=1  
ray start --head --log-to-driver

### Monitoring and Observability

1. Metrics Collection:

# Custom metrics for scheduling performance  
import ray  
from ray.util.metrics import Counter, Histogram  
  
scheduling\_latency = Histogram(  
 "ray\_scheduling\_latency\_seconds",  
 description="Time from task submission to scheduling",  
 boundaries=[0.001, 0.01, 0.1, 1.0, 10.0]  
)  
  
task\_queue\_size = Counter(  
 "ray\_task\_queue\_size",  
 description="Number of tasks in scheduling queue"  
)

2. Dashboard Integration:

* Use Ray Dashboard for real-time cluster monitoring
* Monitor resource utilization trends
* Track placement group creation success rates
* Observe task scheduling patterns

This comprehensive guide covers Ray's distributed scheduling system from architecture to implementation details, providing developers and operators with the knowledge needed to effectively use and optimize Ray's scheduling capabilities in production environments.

Chapter 2: Part I: Ray Fundamentals

# Chapter 2: The Ray Driver System

# Ray Driver - Comprehensive Technical Guide

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## Introduction

The Ray driver is like the conductor of an orchestra - it coordinates all the distributed computation in your Ray cluster. When you run a Python script with ray.init(), that script becomes the driver process. The driver is responsible for submitting tasks, creating actors, managing object references, and collecting results from the distributed cluster.

### What Makes the Ray Driver Special?

Centralized Control with Distributed Execution: The driver provides a single point of control for your distributed program while execution happens across many machines. Think of it as the "brain" that sends instructions to "hands" (workers) throughout the cluster.

Seamless Local-to-Distributed: Your Python code looks almost identical whether running locally or on a 1000-node cluster. The driver handles all the complexity of distribution transparently.

Fault-Tolerant Coordination: The driver can recover from worker failures, network partitions, and other distributed system challenges while maintaining program correctness.

### Core Driver Responsibilities

graph TB  
 subgraph "🎭 Driver Process"  
 SCRIPT["Python Script<br/>📝 Your application code"]  
 RAY\_API["Ray API Layer<br/>🔧 @ray.remote decorators"]  
 CORE\_WORKER["CoreWorker<br/>🧠 Driver's execution engine"]  
 end  
   
 subgraph "🌐 Cluster Coordination"  
 TASK\_SUB["Task Submission<br/>📋 Distribute work"]  
 ACTOR\_MGT["Actor Management<br/>🎭 Create/destroy actors"]  
 OBJ\_MGT["Object Management<br/>💾 Track references"]  
 RESULT\_COL["Result Collection<br/>📊 Gather outputs"]  
 end  
   
 subgraph "🔗 Communication Channels"  
 GCS\_CONN["GCS Connection<br/>🏛️ Global state"]  
 RAYLET\_CONN["Raylet Connections<br/>🔧 Local execution"]  
 OBJ\_STORE\_CONN["Object Store<br/>💿 Data storage"]  
 end  
   
 SCRIPT --> RAY\_API  
 RAY\_API --> CORE\_WORKER  
 CORE\_WORKER --> TASK\_SUB  
 CORE\_WORKER --> ACTOR\_MGT  
 CORE\_WORKER --> OBJ\_MGT  
 CORE\_WORKER --> RESULT\_COL  
   
 TASK\_SUB --> GCS\_CONN  
 ACTOR\_MGT --> GCS\_CONN  
 OBJ\_MGT --> RAYLET\_CONN  
 RESULT\_COL --> OBJ\_STORE\_CONN  
   
 style SCRIPT fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style CORE\_WORKER fill:#f3e5f5,stroke:#4a148c,stroke-width:3px,color:#000  
 style TASK\_SUB fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style ACTOR\_MGT fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style OBJ\_MGT fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style RESULT\_COL fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style GCS\_CONN fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style RAYLET\_CONN fill:#fff8e1,stroke:#f57c00,stroke-width:2px,color:#000  
 style OBJ\_STORE\_CONN fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

## Driver Architecture Overview

### High-Level Architecture

The Ray driver is built on a multi-layered architecture where each layer handles specific aspects of distributed computing:

graph TB  
 subgraph "🎯 Application Layer"  
 USER\_CODE["User Python Code<br/>📝 Your business logic"]  
 RAY\_DECORATORS["@ray.remote Functions/Classes<br/>🎭 Distributed annotations"]  
 end  
   
 subgraph "🔧 Ray API Layer"  
 RAY\_GET["ray.get()<br/>📥 Retrieve results"]  
 RAY\_PUT["ray.put()<br/>📤 Store objects"]  
 RAY\_WAIT["ray.wait()<br/>⏳ Wait for completion"]  
 RAY\_REMOTE["ray.remote()<br/>🚀 Submit work"]  
 end  
   
 subgraph "🧠 Core Worker Layer"  
 TASK\_MANAGER["Task Manager<br/>📋 Track submissions"]  
 ACTOR\_MANAGER["Actor Manager<br/>🎭 Lifecycle management"]  
 OBJECT\_MANAGER["Object Manager<br/>💾 Reference tracking"]  
 REF\_COUNTER["Reference Counter<br/>🔢 Memory management"]  
 end  
   
 subgraph "🌐 Transport Layer"  
 RPC\_CLIENT["RPC Client<br/>📞 Remote calls"]  
 SERIALIZER["Serialization<br/>📦 Data encoding"]  
 CORE\_WORKER\_CLIENT["CoreWorker Client<br/>🔗 Internal communication"]  
 end  
   
 subgraph "🏛️ Cluster Services"  
 GCS["Global Control Service<br/>🏛️ Cluster metadata"]  
 RAYLET["Raylet<br/>🔧 Local scheduling"]  
 OBJECT\_STORE["Object Store<br/>💿 Distributed storage"]  
 end  
   
 USER\_CODE --> RAY\_DECORATORS  
 RAY\_DECORATORS --> RAY\_GET  
 RAY\_DECORATORS --> RAY\_PUT  
 RAY\_DECORATORS --> RAY\_WAIT  
 RAY\_DECORATORS --> RAY\_REMOTE  
   
 RAY\_GET --> TASK\_MANAGER  
 RAY\_PUT --> OBJECT\_MANAGER  
 RAY\_WAIT --> TASK\_MANAGER  
 RAY\_REMOTE --> TASK\_MANAGER  
 RAY\_REMOTE --> ACTOR\_MANAGER  
   
 TASK\_MANAGER --> RPC\_CLIENT  
 ACTOR\_MANAGER --> RPC\_CLIENT  
 OBJECT\_MANAGER --> SERIALIZER  
 REF\_COUNTER --> CORE\_WORKER\_CLIENT  
   
 RPC\_CLIENT --> GCS  
 RPC\_CLIENT --> RAYLET  
 SERIALIZER --> OBJECT\_STORE  
 CORE\_WORKER\_CLIENT --> RAYLET  
   
 style USER\_CODE fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style RAY\_DECORATORS fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style TASK\_MANAGER fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style ACTOR\_MANAGER fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style OBJECT\_MANAGER fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style GCS fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style RAYLET fill:#fff8e1,stroke:#f57c00,stroke-width:2px,color:#000  
 style OBJECT\_STORE fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

### Core Components Deep Dive

#### 1. CoreWorker - The Heart of the Driver

Location: src/ray/core\_worker/core\_worker.h and src/ray/core\_worker/core\_worker.cc

The CoreWorker is the most important component of the driver. Think of it as the driver's "execution engine" that handles all distributed operations.

class CoreWorker {  
 public:  
 /// Constructor for driver process  
 CoreWorker(const CoreWorkerOptions &options, const WorkerID &worker\_id);  
   
 /// Submit a task for remote execution  
 Status SubmitTask(const RayFunction &function,  
 const std::vector<std::unique\_ptr<TaskArg>> &args,  
 const TaskOptions &task\_options,  
 std::vector<rpc::ObjectReference> \*returned\_refs);  
   
 /// Create an actor  
 Status CreateActor(const RayFunction &function,  
 const std::vector<std::unique\_ptr<TaskArg>> &args,  
 const ActorCreationOptions &actor\_creation\_options,  
 std::vector<rpc::ObjectReference> \*returned\_refs);  
   
 /// Get objects from the object store  
 Status Get(const std::vector<ObjectID> &ids,  
 int64\_t timeout\_ms,  
 std::vector<std::shared\_ptr<RayObject>> \*results);  
   
 /// Put an object into the object store  
 Status Put(const RayObject &object,  
 const std::vector<ObjectID> &contained\_object\_ids,  
 ObjectID \*object\_id);  
};

What the CoreWorker Does (In Simple Terms):

* \*\*Task Coordinator\*\*: When you call a @ray.remote function, CoreWorker packages it up and sends it to the right worker
* \*\*Object Tracker\*\*: Keeps track of all the data objects your program creates and where they're stored
* \*\*Communication Hub\*\*: Manages all the network connections to GCS, raylets, and other workers
* \*\*Memory Manager\*\*: Handles garbage collection of distributed objects when they're no longer needed

#### 2. Task Management System

Location: src/ray/core\_worker/task\_manager.h

class TaskManager {  
 private:  
 /// Map from task ID to task specification and metadata  
 absl::flat\_hash\_map<TaskID, TaskSpec> submittable\_tasks\_;  
   
 /// Tasks that have been submitted but not yet completed  
 absl::flat\_hash\_map<TaskID, rpc::TaskStatus> pending\_tasks\_;  
   
 public:  
 /// Add a task that is pending execution  
 void AddPendingTask(const TaskID &task\_id,  
 const TaskSpec &spec,  
 const std::string &call\_site);  
   
 /// Mark a task as completed and handle its return values  
 void CompletePendingTask(const TaskID &task\_id,  
 const rpc::PushTaskReply &reply,  
 const rpc::Address &worker\_addr);  
   
 /// Handle task failure and potential retry  
 void FailPendingTask(const TaskID &task\_id,  
 rpc::ErrorType error\_type,  
 const Status \*status);  
};

#### 3. Actor Management System

Location: src/ray/core\_worker/actor\_manager.h

class ActorManager {  
 private:  
 /// Map from actor ID to actor handle information  
 absl::flat\_hash\_map<ActorID, ActorHandle> actor\_handles\_;  
   
 /// Actors created by this worker  
 absl::flat\_hash\_map<ActorID, std::unique\_ptr<ActorCreationState>> created\_actors\_;  
   
 public:  
 /// Create a new actor  
 Status CreateActor(const TaskSpec &task\_spec,  
 const gcs::ActorCreationOptions &options,  
 std::vector<rpc::ObjectReference> \*returned\_refs);  
   
 /// Submit a task to an existing actor  
 Status SubmitActorTask(const ActorID &actor\_id,  
 const TaskSpec &task\_spec,  
 std::vector<rpc::ObjectReference> \*returned\_refs);  
   
 /// Handle actor death and cleanup  
 void HandleActorStateNotification(const ActorID &actor\_id,  
 const gcs::ActorTableData &actor\_data);  
};

## Driver Lifecycle Deep Dive

### Phase 1: Initialization (`ray.init()`)

When you call ray.init(), a complex initialization sequence begins:

sequenceDiagram  
 participant U as User Script  
 participant API as Ray API  
 participant CW as CoreWorker  
 participant GCS as Global Control Service  
 participant R as Local Raylet  
 participant OS as Object Store  
   
 U->>API: ray.init()  
 Note over API: Parse configuration options  
 API->>CW: Create CoreWorker instance  
 CW->>GCS: Connect to GCS  
 GCS-->>CW: Return cluster metadata  
 CW->>R: Connect to local raylet  
 R-->>CW: Return worker registration  
 CW->>OS: Connect to object store  
 OS-->>CW: Return object store handle  
 CW->>GCS: Register as driver  
 GCS-->>CW: Assign WorkerID  
 CW-->>API: Initialization complete  
 API-->>U: Ready for distributed computing  
   
 Note over U,OS: Driver is now fully initialized and connected

Detailed Initialization Steps:

1. Configuration Resolution: Ray determines cluster address, resources, and other settings 2. CoreWorker Creation: The main driver execution engine is initialized 3. GCS Connection: Establishes connection to cluster metadata service 4. Raylet Connection: Connects to local scheduling and execution service 5. Object Store Connection: Sets up shared memory access for data storage 6. Driver Registration: Registers with GCS as a special "driver" worker type

# From python/ray/\_private/worker.py  
def init(address=None,   
 num\_cpus=None,  
 num\_gpus=None,  
 resources=None,  
 object\_store\_memory=None,  
 local\_mode=False,  
 \*\*kwargs):  
 """Initialize Ray for distributed computing."""  
   
 # Step 1: Process configuration  
 config = \_load\_config(kwargs)  
   
 # Step 2: Start or connect to cluster  
 if address is None:  
 # Start local cluster  
 \_global\_node = ray.\_private.node.Node(  
 head=True,  
 shutdown\_at\_exit=True,  
 ray\_params=ray\_params)  
 else:  
 # Connect to existing cluster  
 ray\_params.update\_if\_absent(redis\_address=address)  
   
 # Step 3: Initialize CoreWorker  
 worker = Worker()  
 worker.mode = LOCAL\_MODE if local\_mode else WORKER\_MODE  
   
 # Step 4: Connect to services  
 gcs\_client = GcsClient(address=gcs\_address)  
 worker.gcs\_client = gcs\_client  
   
 # Step 5: Register as driver  
 worker.worker\_id = ray.\_private.utils.compute\_driver\_id\_from\_job(  
 job\_id, ray\_params.driver\_id)  
   
 # CoreWorker handles the rest of initialization  
 \_global\_worker = worker  
 worker.check\_connected()

### Phase 2: Task and Actor Submission

#### Task Submission Flow

graph TD  
 subgraph "🎯 Python Level"  
 FUNC\_CALL["Function Call<br/>result = f.remote(args)"]  
 RAY\_GET["ray.get(result)<br/>Retrieve value"]  
 end  
   
 subgraph "🔧 Ray API Layer"  
 REMOTE\_FUNC["RemoteFunction<br/>Decorated function wrapper"]  
 TASK\_SPEC["TaskSpec Creation<br/>Serialize function + args"]  
 end  
   
 subgraph "🧠 CoreWorker"  
 TASK\_MANAGER["TaskManager<br/>Track pending tasks"]  
 RPC\_CLIENT["RPC Client<br/>Send to raylet"]  
 OBJ\_MANAGER["ObjectManager<br/>Handle return refs"]  
 end  
   
 subgraph "🌐 Cluster Services"  
 RAYLET["Raylet Scheduler<br/>Find worker"]  
 WORKER["Worker Process<br/>Execute task"]  
 OBJECT\_STORE["Object Store<br/>Store results"]  
 end  
   
 FUNC\_CALL --> REMOTE\_FUNC  
 REMOTE\_FUNC --> TASK\_SPEC  
 TASK\_SPEC --> TASK\_MANAGER  
 TASK\_MANAGER --> RPC\_CLIENT  
 RPC\_CLIENT --> RAYLET  
 RAYLET --> WORKER  
 WORKER --> OBJECT\_STORE  
 OBJECT\_STORE --> OBJ\_MANAGER  
 OBJ\_MANAGER --> RAY\_GET  
   
 style FUNC\_CALL fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style TASK\_SPEC fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style TASK\_MANAGER fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style RAYLET fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style WORKER fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style OBJECT\_STORE fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

Code Deep Dive - Task Submission:

// From src/ray/core\_worker/core\_worker.cc  
Status CoreWorker::SubmitTask(const RayFunction &function,  
 const std::vector<std::unique\_ptr<TaskArg>> &args,  
 const TaskOptions &task\_options,  
 std::vector<rpc::ObjectReference> \*returned\_refs) {  
   
 // Step 1: Create unique task ID  
 const TaskID task\_id = TaskID::FromRandom();  
   
 // Step 2: Build task specification  
 TaskSpecBuilder builder;  
 builder.SetCommonTaskSpec(task\_id, function.GetLanguage(),   
 function.GetFunctionDescriptor(),  
 job\_id\_, task\_id, /\*parent\_counter=\*/0,   
 caller\_id\_, rpc\_address\_,   
 task\_options.resources,  
 task\_options.placement\_group\_bundle\_index);  
   
 // Step 3: Add function arguments  
 for (const auto &arg : args) {  
 if (arg->IsPassedByReference()) {  
 builder.AddByRefArg(arg->GetReference());  
 } else {  
 builder.AddByValueArg(\*arg->GetValue());  
 }  
 }  
   
 const TaskSpec task\_spec = builder.Build();  
   
 // Step 4: Generate return object references  
 for (int i = 0; i < task\_spec.NumReturns(); i++) {  
 returned\_refs->emplace\_back();  
 returned\_refs->back().set\_object\_id(  
 ObjectID::FromIndex(task\_id, i + 1).Binary());  
 }  
   
 // Step 5: Submit to task manager for tracking  
 task\_manager\_->AddPendingTask(task\_id, task\_spec, "");  
   
 // Step 6: Send to raylet for scheduling  
 return raylet\_client\_->SubmitTask(task\_spec, task\_options.concurrency\_group\_name);  
}

### Phase 3: Result Collection and Object Management

#### Object Reference System

Ray uses a sophisticated object reference system where the driver tracks references to distributed objects:

graph TB  
 subgraph "🎯 Driver Process"  
 USER\_REF["ObjectRef<br/>🏷️ User's handle"]  
 REF\_COUNTER["Reference Counter<br/>🔢 Track usage"]  
 OBJ\_MANAGER["Object Manager<br/>💾 Local tracking"]  
 end  
   
 subgraph "🌐 Distributed Storage"  
 OBJ\_STORE\_1["Object Store 1<br/>💿 Node A storage"]  
 OBJ\_STORE\_2["Object Store 2<br/>💿 Node B storage"]  
 OBJ\_STORE\_3["Object Store 3<br/>💿 Node C storage"]  
 end  
   
 subgraph "🏛️ Global Tracking"  
 GCS\_OBJ\_MGR["GCS Object Manager<br/>🗂️ Global object directory"]  
 OWNER\_INFO["Owner Information<br/>👤 Who created object"]  
 LOCATION\_INFO["Location Information<br/>📍 Where object lives"]  
 end  
   
 USER\_REF --> REF\_COUNTER  
 REF\_COUNTER --> OBJ\_MANAGER  
 OBJ\_MANAGER --> GCS\_OBJ\_MGR  
   
 GCS\_OBJ\_MGR --> OWNER\_INFO  
 GCS\_OBJ\_MGR --> LOCATION\_INFO  
   
 LOCATION\_INFO --> OBJ\_STORE\_1  
 LOCATION\_INFO --> OBJ\_STORE\_2  
 LOCATION\_INFO --> OBJ\_STORE\_3  
   
 style USER\_REF fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style REF\_COUNTER fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style OBJ\_MANAGER fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style GCS\_OBJ\_MGR fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style OBJ\_STORE\_1 fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style OBJ\_STORE\_2 fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000  
 style OBJ\_STORE\_3 fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000

### Phase 4: Cleanup and Shutdown

When the driver shuts down, it must carefully clean up all distributed resources:

# From python/ray/\_private/worker.py   
def shutdown(verbose=True):  
 """Clean shutdown of Ray driver."""  
   
 # Step 1: Cancel all pending tasks  
 \_global\_worker.core\_worker.cancel\_all\_tasks()  
   
 # Step 2: Destroy all actors created by this driver  
 for actor\_id in \_global\_worker.actor\_handles:  
 \_global\_worker.core\_worker.kill\_actor(actor\_id, no\_restart=True)  
   
 # Step 3: Clean up object references  
 \_global\_worker.core\_worker.shutdown()  
   
 # Step 4: Disconnect from cluster services  
 if \_global\_worker.gcs\_client:  
 \_global\_worker.gcs\_client.disconnect()  
   
 # Step 5: Cleanup local services if running standalone  
 if \_global\_node:  
 \_global\_node.kill\_all\_processes()

## Communication Mechanisms

The Ray driver uses multiple communication channels optimized for different types of operations:

### 1. Driver-to-GCS Communication

Purpose: Cluster metadata, actor lifecycle, job management

sequenceDiagram  
 participant D as Driver  
 participant GCS as GCS Server  
 participant DB as Metadata Store  
   
 Note over D,DB: Actor Creation  
 D->>GCS: CreateActor request  
 GCS->>DB: Store actor metadata  
 GCS-->>D: Actor created (ActorID)  
   
 Note over D,DB: Global State Queries  
 D->>GCS: Get cluster resources  
 GCS->>DB: Query resource state  
 GCS-->>D: Resource availability  
   
 Note over D,DB: Job Management  
 D->>GCS: Submit job metadata  
 GCS->>DB: Store job info  
 GCS-->>D: Job registered

Code Example - GCS Client:

// From src/ray/gcs/gcs\_client/gcs\_client.h  
class GcsClient {  
 public:  
 /// Create an actor via GCS  
 Status CreateActor(const TaskSpec &task\_spec,  
 const gcs::ActorCreationOptions &options,  
 std::vector<rpc::ObjectReference> \*returned\_refs) {  
   
 rpc::CreateActorRequest request;  
 request.mutable\_task\_spec()->CopyFrom(task\_spec.GetMessage());  
 request.mutable\_options()->CopyFrom(options);  
   
 return actor\_accessor\_->AsyncCreateActor(  
 request,  
 [this, returned\_refs](Status status, const rpc::CreateActorReply &reply) {  
 if (status.ok()) {  
 // Extract actor handle and return references  
 for (const auto &ref : reply.returned\_refs()) {  
 returned\_refs->push\_back(ref);  
 }  
 }  
 });  
 }  
};

### 2. Driver-to-Raylet Communication

Purpose: Task submission, resource requests, local scheduling

graph LR  
 subgraph "🎯 Driver Operations"  
 SUBMIT\_TASK["Submit Task<br/>📋 Function + Args"]  
 REQUEST\_WORKER["Request Worker<br/>👤 Need execution slot"]  
 GET\_OBJECT["Get Object<br/>📥 Retrieve data"]  
 end  
   
 subgraph "🔧 Raylet Services"  
 SCHEDULER["Task Scheduler<br/>⚖️ Find worker"]  
 WORKER\_POOL["Worker Pool<br/>👥 Manage processes"]  
 OBJ\_MGR["Object Manager<br/>💾 Local objects"]  
 end  
   
 subgraph "📞 Communication Layer"  
 RPC\_CHANNEL["gRPC Channel<br/>🔗 Persistent connection"]  
 TASK\_QUEUE["Task Queue<br/>📬 Pending work"]  
 CALLBACK\_MGR["Callback Manager<br/>📞 Async responses"]  
 end  
   
 SUBMIT\_TASK --> RPC\_CHANNEL  
 REQUEST\_WORKER --> RPC\_CHANNEL  
 GET\_OBJECT --> RPC\_CHANNEL  
   
 RPC\_CHANNEL --> SCHEDULER  
 RPC\_CHANNEL --> WORKER\_POOL  
 RPC\_CHANNEL --> OBJ\_MGR  
   
 SCHEDULER --> TASK\_QUEUE  
 WORKER\_POOL --> CALLBACK\_MGR  
 OBJ\_MGR --> CALLBACK\_MGR  
   
 style SUBMIT\_TASK fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style REQUEST\_WORKER fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style GET\_OBJECT fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style SCHEDULER fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style WORKER\_POOL fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style OBJ\_MGR fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

### 3. Driver-to-Object Store Communication

Purpose: High-bandwidth data transfer, shared memory access

The driver accesses the object store through optimized shared memory interfaces:

// From src/ray/object\_store/plasma/client.h  
class PlasmaClient {  
 public:  
 /// Get objects from local object store  
 Status Get(const std::vector<ObjectID> &object\_ids,  
 int64\_t timeout\_ms,  
 std::vector<ObjectBuffer> \*object\_buffers) {  
   
 // Step 1: Check local availability  
 std::vector<plasma::ObjectBuffer> results(object\_ids.size());  
   
 // Step 2: Wait for objects if needed  
 Status wait\_status = impl\_->Wait(object\_ids, timeout\_ms, &results);  
   
 // Step 3: Map shared memory segments  
 for (size\_t i = 0; i < results.size(); i++) {  
 if (results[i].data != nullptr) {  
 object\_buffers->emplace\_back(results[i].data, results[i].data\_size);  
 }  
 }  
   
 return wait\_status;  
 }  
   
 /// Put object into local object store   
 Status Put(const ray::ObjectID &object\_id,  
 const uint8\_t \*data,  
 size\_t data\_size) {  
   
 // Step 1: Create plasma object  
 std::shared\_ptr<Buffer> buffer;  
 Status create\_status = impl\_->Create(object\_id, data\_size, &buffer);  
   
 // Step 2: Copy data into shared memory  
 std::memcpy(buffer->mutable\_data(), data, data\_size);  
   
 // Step 3: Seal object (make immutable)  
 return impl\_->Seal(object\_id);  
 }  
};

## Driver-GCS Integration

The Global Control Service (GCS) acts as the cluster's "central nervous system" and the driver maintains a close relationship with it:

### Actor Lifecycle Management

sequenceDiagram  
 participant D as Driver  
 participant GCS as GCS Server  
 participant SM as State Manager  
 participant R as Raylet  
 participant W as Worker  
   
 Note over D,W: Actor Creation Flow  
 D->>GCS: CreateActor(class, args, resources)  
 GCS->>SM: Store actor metadata  
 GCS->>R: Schedule actor placement  
 R->>W: Start worker process  
 W->>GCS: Register actor ready  
 GCS-->>D: Return ActorHandle  
   
 Note over D,W: Actor Method Calls  
 D->>R: Submit actor task  
 R->>W: Execute method  
 W-->>R: Return result  
 R-->>D: Task complete  
   
 Note over D,W: Actor Death Handling  
 W->>GCS: Actor died notification  
 GCS->>SM: Update actor state  
 GCS->>D: Notify actor dead  
 D->>D: Clean up actor handle

### Job Management and Driver Registration

// From src/ray/gcs/gcs\_server/gcs\_job\_manager.h  
class GcsJobManager {  
 public:  
 /// Register a new driver/job with the cluster  
 void HandleAddJob(const rpc::AddJobRequest &request,  
 rpc::AddJobReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback) {  
   
 // Extract job information  
 const auto &job\_data = request.data();  
 const JobID job\_id = JobID::FromBinary(job\_data.job\_id());  
   
 // Store job metadata  
 auto job\_table\_data = std::make\_shared<rpc::JobTableData>();  
 job\_table\_data->CopyFrom(job\_data);  
   
 // Add to job table in persistent store  
 auto status = gcs\_table\_storage\_->JobTable().Put(  
 job\_id,  
 \*job\_table\_data,  
 [send\_reply\_callback, reply](Status status) {  
 reply->set\_success(status.ok());  
 send\_reply\_callback(status, nullptr, nullptr);  
 });  
 }  
};

### Resource Management Integration

The driver coordinates with GCS for cluster-wide resource management:

# Example: Driver requesting specific resources  
@ray.remote(num\_cpus=4, num\_gpus=1, memory=8000)  
def gpu\_task(data):  
 # This task needs specific resources  
 return process\_on\_gpu(data)  
  
# Behind the scenes, the driver:  
# 1. Registers resource requirements with GCS  
# 2. GCS finds nodes with available resources   
# 3. GCS tells raylet to schedule the task  
# 4. Raylet allocates resources and starts worker

## Code Navigation Guide

### Key Entry Points for Driver Functionality

#### 1. Python API Layer

Location: python/ray/\_private/worker.py

This is where the user-facing Ray API is implemented:

# Main initialization  
def init(...) -> ray.init()  
  
# Task submission   
class RemoteFunction:  
 def remote(self, \*args, \*\*kwargs) -> ObjectRef  
  
# Object operations  
def get(object\_refs, timeout=None) -> ray.get()  
def put(value) -> ray.put()  
def wait(object\_refs, num\_returns=1, timeout=None) -> ray.wait()

#### 2. CoreWorker Implementation

Location: src/ray/core\_worker/core\_worker.{h,cc}

The main C++ driver implementation:

// Key methods for understanding driver behavior:  
Status CoreWorker::SubmitTask(...) // Task submission logic  
Status CoreWorker::CreateActor(...) // Actor creation logic   
Status CoreWorker::Get(...) // Object retrieval logic  
Status CoreWorker::Put(...) // Object storage logic

#### 3. Task and Actor Management

Location: src/ray/core\_worker/task\_manager.{h,cc} and src/ray/core\_worker/actor\_manager.{h,cc}

class TaskManager {  
 void AddPendingTask(...) // Track submitted tasks  
 void CompletePendingTask(...) // Handle task completion  
 void FailPendingTask(...) // Handle task failures  
};  
  
class ActorManager {  
 Status CreateActor(...) // Actor lifecycle start  
 Status SubmitActorTask(...) // Send methods to actors  
 void HandleActorStateNotification(...) // React to actor events  
};

#### 4. Communication Layers

Location: src/ray/rpc/ and src/ray/core\_worker/transport/

// GCS communication  
class GcsClient : public GcsClientInterface {...}  
  
// Raylet communication   
class CoreWorkerRayletTaskSubmitter {...}  
  
// Direct worker communication  
class CoreWorkerDirectTaskSubmitter {...}

### Debugging and Instrumentation Points

#### 1. Driver State Inspection

# Get current driver state  
import ray  
worker = ray.\_private.worker.global\_worker  
  
# View pending tasks  
print(f"Pending tasks: {len(worker.core\_worker.get\_all\_pending\_tasks())}")  
  
# View actor handles   
print(f"Actor handles: {len(worker.actor\_handles)}")  
  
# View object references  
print(f"Object refs in scope: {worker.core\_worker.get\_objects\_in\_scope()}")

#### 2. Enable Detailed Logging

import logging  
logging.getLogger("ray.core\_worker").setLevel(logging.DEBUG)  
logging.getLogger("ray.gcs\_client").setLevel(logging.DEBUG)

#### 3. Ray Status and Debugging Tools

# View cluster state from driver perspective  
ray status  
  
# Get detailed driver information  
ray logs --actor-id <driver-worker-id>  
  
# Monitor object references  
ray memory --stats-only

This comprehensive guide provides the foundation for understanding Ray's driver implementation. The driver serves as the central coordinator for distributed Ray applications, managing task submission, actor lifecycles, object references, and communication with cluster services through sophisticated APIs and communication protocols.

Chapter 3: Part I: Ray Fundamentals

# Chapter 3: Task Lifecycle and Management

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1. [Introduction](#introduction) 2. [Task Architecture Overview](#task-architecture-overview) 3. [Task Creation and Submission](#task-creation-and-submission) 4. [Task Scheduling and Placement](#task-scheduling-and-placement) 5. [Task Execution Engine](#task-execution-engine) 6. [Task Dependencies and Lineage](#task-dependencies-and-lineage) 7. [Error Handling and Retry Logic](#error-handling-and-retry-logic) 8. [Performance Optimization](#performance-optimization) 9. [Code Navigation Guide](#code-navigation-guide)

## Introduction

Ray tasks are the fundamental units of computation in the Ray ecosystem. Think of a task as a function call that can run anywhere in your cluster - it could execute on your local machine, a machine in another data center, or even on a different cloud provider. Tasks are stateless, immutable, and designed for maximum parallelism.

### What Makes Ray Tasks Special?

Stateless Execution: Tasks don't maintain state between calls, making them easy to distribute, retry, and scale horizontally.

Automatic Parallelism: When you call a remote function, Ray automatically distributes the work across available workers without you having to think about threads, processes, or network communication.

Fault Tolerance: If a task fails, Ray can automatically retry it on different machines, ensuring your computation completes even in the face of hardware failures.

Efficient Data Sharing: Tasks can share large datasets efficiently through Ray's distributed object store without copying data unnecessarily.

### Core Task Concepts

graph TB  
 subgraph "📋 Task Lifecycle"  
 SUBMISSION["Task Submission<br/>📤 Driver calls remote function"]  
 SCHEDULING["Task Scheduling<br/>⚖️ Find suitable worker"]  
 EXECUTION["Task Execution<br/>⚡ Run function logic"]  
 COMPLETION["Task Completion<br/>✅ Store results"]  
 end  
   
 subgraph "🔧 Task Components"  
 TASK\_SPEC["Task Specification<br/>📋 Function + arguments"]  
 OBJECT\_REFS["Object References<br/>🏷️ Future results"]  
 DEPENDENCIES["Dependencies<br/>🔗 Input requirements"]  
 RESOURCES["Resource Requirements<br/>💰 CPU/GPU/Memory"]  
 end  
   
 subgraph "🌐 Execution Context"  
 WORKER\_PROCESS["Worker Process<br/>🔧 Isolated execution"]  
 OBJECT\_STORE["Object Store<br/>💿 Shared data"]  
 TASK\_MANAGER["Task Manager<br/>📊 Lifecycle tracking"]  
 end  
   
 SUBMISSION --> SCHEDULING  
 SCHEDULING --> EXECUTION  
 EXECUTION --> COMPLETION  
   
 TASK\_SPEC --> WORKER\_PROCESS  
 OBJECT\_REFS --> OBJECT\_STORE  
 DEPENDENCIES --> TASK\_MANAGER  
 RESOURCES --> WORKER\_PROCESS  
   
 style SUBMISSION fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style EXECUTION fill:#e8f5e8,stroke:#1b5e20,stroke-width:3px,color:#000  
 style TASK\_SPEC fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style WORKER\_PROCESS fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000

## Task Architecture Overview

### High-Level Task System Architecture

Ray's task system is built on multiple layers that handle different aspects of distributed task execution:

graph TB  
 subgraph "🎯 Application Layer"  
 USER\_FUNC["@ray.remote Function<br/>📝 User-defined computation"]  
 REMOTE\_CALL["Function.remote()<br/>📞 Asynchronous invocation"]  
 RAY\_GET["ray.get()<br/>📥 Result retrieval"]  
 end  
   
 subgraph "🔧 Ray API Layer"  
 TASK\_FACTORY["Task Factory<br/>🏗️ Task specification creation"]  
 OBJECT\_MGR["Object Manager<br/>🏷️ Reference tracking"]  
 SERIALIZER["Serialization<br/>📦 Data encoding"]  
 end  
   
 subgraph "�� Core Worker Layer"  
 TASK\_SUBMITTER["Task Submitter<br/>📋 Dispatch coordination"]  
 DEPENDENCY\_MGR["Dependency Manager<br/>🔗 Input resolution"]  
 RESULT\_MGR["Result Manager<br/>📊 Output handling"]  
 end  
   
 subgraph "🌐 Cluster Services"  
 TASK\_SCHEDULER["Task Scheduler<br/>⚖️ Worker selection"]  
 RAYLET["Raylet<br/>🔧 Local coordination"]  
 WORKER\_POOL["Worker Pool<br/>👥 Process management"]  
 end  
   
 subgraph "⚡ Execution Layer"  
 WORKER\_PROCESS["Worker Process<br/>🎯 Task execution"]  
 FUNCTION\_RUNTIME["Function Runtime<br/>⚙️ Python execution"]  
 OBJECT\_STORE["Object Store<br/>💿 Data storage"]  
 end  
   
 USER\_FUNC --> TASK\_FACTORY  
 REMOTE\_CALL --> OBJECT\_MGR  
 RAY\_GET --> SERIALIZER  
   
 TASK\_FACTORY --> TASK\_SUBMITTER  
 OBJECT\_MGR --> DEPENDENCY\_MGR  
 SERIALIZER --> RESULT\_MGR  
   
 TASK\_SUBMITTER --> TASK\_SCHEDULER  
 DEPENDENCY\_MGR --> RAYLET  
 RESULT\_MGR --> WORKER\_POOL  
   
 TASK\_SCHEDULER --> WORKER\_PROCESS  
 RAYLET --> FUNCTION\_RUNTIME  
 WORKER\_POOL --> OBJECT\_STORE  
   
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 style REMOTE\_CALL fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style TASK\_SUBMITTER fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style TASK\_SCHEDULER fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style WORKER\_PROCESS fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000

### Task vs Actor Comparison

Understanding the differences between tasks and actors is crucial for designing Ray applications:

graph LR  
 subgraph "📋 Task Model"  
 TASK\_STATELESS["Stateless<br/>🔄 No persistent memory"]  
 TASK\_IMMUTABLE["Immutable<br/>🔒 Cannot change state"]  
 TASK\_PARALLEL["Massively Parallel<br/>⚡ Unlimited instances"]  
 TASK\_EPHEMERAL["Ephemeral<br/>⏰ Short-lived execution"]  
 end  
   
 subgraph "🎭 Actor Model"  
 ACTOR\_STATEFUL["Stateful<br/>💾 Persistent memory"]  
 ACTOR\_MUTABLE["Mutable<br/>🔧 Can change state"]  
 ACTOR\_SEQUENTIAL["Sequential<br/>📋 Ordered execution"]  
 ACTOR\_PERSISTENT["Persistent<br/>🏠 Long-lived process"]  
 end  
   
 subgraph "🎯 Use Cases"  
 BATCH\_PROCESSING["Batch Processing<br/>📊 Data transformation"]  
 STREAMING["Streaming Computation<br/>🌊 Real-time processing"]  
 STATEFUL\_SERVICE["Stateful Services<br/>🏪 Databases, caches"]  
 COORDINATION["Coordination<br/>🤝 System orchestration"]  
 end  
   
 TASK\_STATELESS --> BATCH\_PROCESSING  
 TASK\_PARALLEL --> STREAMING  
 ACTOR\_STATEFUL --> STATEFUL\_SERVICE  
 ACTOR\_PERSISTENT --> COORDINATION  
   
 style TASK\_STATELESS fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style TASK\_PARALLEL fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style ACTOR\_STATEFUL fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style ACTOR\_PERSISTENT fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style BATCH\_PROCESSING fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style STATEFUL\_SERVICE fill:#fce4ec,stroke:#c2185b,stroke-width:2px,color:#000

## Task Creation and Submission

### Phase 1: Function Registration

When you decorate a function with @ray.remote, Ray prepares it for distributed execution:

# User code  
@ray.remote(num\_cpus=2, memory=1000)  
def process\_data(data\_chunk, model\_params):  
 """Example computation-intensive task"""  
 import numpy as np  
   
 # Simulate data processing  
 processed = np.array(data\_chunk) \* np.array(model\_params)  
 result = np.sum(processed \*\* 2)  
   
 return {  
 'result': result,  
 'chunk\_size': len(data\_chunk),  
 'processing\_time': time.time()  
 }  
  
# Submit tasks  
data\_chunks = [[1, 2, 3], [4, 5, 6], [7, 8, 9]]  
model\_params = [0.1, 0.2, 0.3]  
  
# These calls return immediately with ObjectRefs  
futures = [process\_data.remote(chunk, model\_params) for chunk in data\_chunks]  
  
# Retrieve results when needed  
results = ray.get(futures)

Behind the Scenes - Function Registration:

# From python/ray/\_private/worker.py  
def make\_function\_remote(function, num\_cpus, num\_gpus, memory, \*\*kwargs):  
 """Convert a regular function into a Ray remote function."""  
   
 # Step 1: Create function metadata  
 function\_id = compute\_function\_id(function)  
   
 # Step 2: Register function with driver's core worker  
 driver\_worker = ray.\_private.worker.global\_worker  
 driver\_worker.function\_actor\_manager.export\_function(  
 function, function\_id, num\_cpus, num\_gpus, memory)  
   
 # Step 3: Create remote function wrapper  
 def remote(\*args, \*\*kwargs):  
 return RemoteFunction.\_remote(  
 args=args, kwargs=kwargs,  
 num\_cpus=num\_cpus, num\_gpus=num\_gpus, memory=memory)  
   
 # Step 4: Return enhanced function  
 function.remote = remote  
 return function

### Phase 2: Task Specification Creation

When you call function.remote(), Ray creates a detailed task specification:

sequenceDiagram  
 participant U as User Code  
 participant RF as RemoteFunction  
 participant CW as CoreWorker  
 participant TS as TaskSubmitter  
 participant GCS as GCS  
 participant R as Raylet  
   
 U->>RF: process\_data.remote(chunk, params)  
 RF->>CW: Create task specification  
 CW->>TS: Build TaskSpec with metadata  
 TS->>GCS: Register task dependencies  
 GCS->>R: Forward to appropriate raylet  
 R->>R: Queue task for scheduling  
 RF-->>U: Return ObjectRef immediately  
   
 Note over U,R: Task is now in the system pipeline

Detailed Task Specification Code:

// From src/ray/core\_worker/core\_worker.cc  
Status CoreWorker::SubmitTask(const RayFunction &function,  
 const std::vector<std::unique\_ptr<TaskArg>> &args,  
 const TaskOptions &task\_options,  
 std::vector<rpc::ObjectReference> \*returned\_refs) {  
   
 // Step 1: Generate unique task ID  
 const TaskID task\_id = TaskID::FromRandom();  
   
 // Step 2: Build comprehensive task specification  
 TaskSpecBuilder builder;  
 builder.SetCommonTaskSpec(  
 task\_id, // Unique identifier  
 function.GetLanguage(), // Python/Java/C++  
 function.GetFunctionDescriptor(), // Function metadata  
 job\_id\_, // Current job  
 TaskID::Nil(), // Parent task (for nested)  
 /\*parent\_counter=\*/0, // Ordering within parent  
 caller\_id\_, // Calling worker ID  
 rpc\_address\_, // Return address  
 task\_options.resources, // Resource requirements  
 task\_options.placement\_group\_bundle\_index // Placement constraints  
 );  
   
 // Step 3: Process function arguments  
 for (size\_t i = 0; i < args.size(); i++) {  
 const auto &arg = args[i];  
 if (arg->IsPassedByReference()) {  
 // Argument is an ObjectRef from another task  
 builder.AddByRefArg(arg->GetReference());  
 } else {  
 // Argument is a direct value (serialized)  
 builder.AddByValueArg(\*arg->GetValue());  
 }  
 }  
   
 const TaskSpec task\_spec = builder.Build();  
   
 // Step 4: Create return object references  
 for (int i = 0; i < task\_spec.NumReturns(); i++) {  
 returned\_refs->emplace\_back();  
 returned\_refs->back().set\_object\_id(  
 ObjectID::FromIndex(task\_id, i + 1).Binary());  
 returned\_refs->back().set\_owner\_id(GetWorkerID().Binary());  
 }  
   
 // Step 5: Submit to task manager for tracking  
 task\_manager\_->AddPendingTask(task\_id, task\_spec, "user\_task");  
   
 // Step 6: Forward to appropriate scheduler  
 return raylet\_client\_->SubmitTask(task\_spec, "");  
}

### Phase 3: Argument Processing and Serialization

Ray carefully handles different types of task arguments:

# Example: Different argument types  
@ray.remote  
def complex\_task(  
 simple\_value, # Serialized directly  
 numpy\_array, # Efficient serialization  
 object\_ref, # Reference to distributed object  
 large\_dataset, # Stored in object store  
 custom\_object # User-defined class  
):  
 # Function body  
 pass  
  
# Different ways to pass arguments  
simple\_result = ray.put("large data") # Explicit put  
array\_result = other\_task.remote() # Task dependency  
large\_data = np.random.random((1000000,)) # Auto-stored  
  
# All argument types in one call  
result = complex\_task.remote(  
 42, # Simple value  
 np.array([1, 2, 3]), # Small array (serialized)  
 array\_result, # ObjectRef dependency  
 large\_data, # Large data (auto-put)  
 MyCustomClass() # Custom object  
)

Argument Processing Logic:

// From src/ray/core\_worker/core\_worker.cc  
std::unique\_ptr<TaskArg> CreateTaskArg(const py::object &obj) {  
 // Check if object is already an ObjectRef  
 if (IsObjectRef(obj)) {  
 ObjectID object\_id = GetObjectID(obj);  
 return std::make\_unique<TaskArgByReference>(object\_id);  
 }  
   
 // Check object size to decide on storage strategy  
 size\_t serialized\_size = GetSerializedSize(obj);  
   
 if (serialized\_size > kObjectStoreThreshold) {  
 // Large object: store in object store and pass by reference  
 ObjectID object\_id;  
 Status status = Put(obj, &object\_id);  
 RAY\_CHECK\_OK(status);  
 return std::make\_unique<TaskArgByReference>(object\_id);  
 } else {  
 // Small object: serialize and pass by value  
 auto serialized\_obj = SerializeObject(obj);  
 return std::make\_unique<TaskArgByValue>(std::move(serialized\_obj));  
 }  
}

## Task Scheduling and Placement

### Cluster-Level Task Scheduling

Ray's task scheduler makes intelligent decisions about where to run tasks:

graph TB  
 subgraph "📊 Scheduling Inputs"  
 TASK\_QUEUE["Task Queue<br/>📋 Pending work"]  
 RESOURCE\_REQ["Resource Requirements<br/>💰 CPU/GPU/Memory"]  
 NODE\_STATE["Node State<br/>🖥️ Available resources"]  
 LOCALITY["Data Locality<br/>📍 Input object locations"]  
 end  
   
 subgraph "🧠 Scheduling Logic"  
 RESOURCE\_MATCHING["Resource Matching<br/>⚖️ Can node handle task?"]  
 LOAD\_BALANCING["Load Balancing<br/>📊 Distribute work evenly"]  
 LOCALITY\_OPT["Locality Optimization<br/>🎯 Minimize data movement"]  
 PRIORITY\_HANDLING["Priority Handling<br/>🔝 Critical tasks first"]  
 end  
   
 subgraph "🎯 Scheduling Decisions"  
 NODE\_SELECTION["Node Selection<br/>🖥️ Best fit worker"]  
 RESOURCE\_ALLOCATION["Resource Allocation<br/>🔒 Reserve capacity"]  
 TASK\_DISPATCH["Task Dispatch<br/>📤 Send to worker"]  
 end  
   
 TASK\_QUEUE --> RESOURCE\_MATCHING  
 RESOURCE\_REQ --> RESOURCE\_MATCHING  
 NODE\_STATE --> LOAD\_BALANCING  
 LOCALITY --> LOCALITY\_OPT  
   
 RESOURCE\_MATCHING --> NODE\_SELECTION  
 LOAD\_BALANCING --> NODE\_SELECTION  
 LOCALITY\_OPT --> RESOURCE\_ALLOCATION  
 PRIORITY\_HANDLING --> TASK\_DISPATCH  
   
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 style RESOURCE\_MATCHING fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style NODE\_SELECTION fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style TASK\_DISPATCH fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000

### Local Task Scheduling (Raylet)

Once a task arrives at a raylet, local scheduling decisions are made:

// From src/ray/raylet/local\_task\_manager.cc  
void LocalTaskManager::ScheduleAndDispatchTasks() {  
 // Step 1: Process tasks waiting for dependencies  
 SchedulePendingTasks();  
   
 // Step 2: Dispatch ready tasks to workers  
 DispatchScheduledTasksToWorkers();  
   
 // Step 3: Handle task completion and cleanup  
 ProcessTaskCompletion();  
}  
  
void LocalTaskManager::SchedulePendingTasks() {  
 auto it = tasks\_to\_schedule\_.begin();  
 while (it != tasks\_to\_schedule\_.end()) {  
 const auto &task\_id = it->first;  
 const auto &task\_spec = it->second;  
   
 // Check if all dependencies are satisfied  
 if (task\_dependency\_manager\_->CheckTaskReady(task\_id)) {  
 // Check if resources are available  
 if (cluster\_resource\_scheduler\_->HasSufficientResource(  
 task\_spec.GetRequiredResources())) {  
   
 // Move to dispatch queue  
 tasks\_to\_dispatch\_[task\_id] = task\_spec;  
 it = tasks\_to\_schedule\_.erase(it);  
   
 // Reserve resources for this task  
 cluster\_resource\_scheduler\_->AllocateTaskResources(  
 task\_id, task\_spec.GetRequiredResources());  
 } else {  
 ++it; // Keep waiting for resources  
 }  
 } else {  
 ++it; // Keep waiting for dependencies  
 }  
 }  
}

### Intelligent Worker Selection

The scheduler considers multiple factors when selecting workers:

graph LR  
 subgraph "🎯 Selection Criteria"  
 RESOURCE\_FIT["Resource Fit<br/>✅ Has required CPU/GPU"]  
 CURRENT\_LOAD["Current Load<br/>📊 Worker utilization"]  
 DATA\_LOCALITY["Data Locality<br/>📍 Input object location"]  
 WORKER\_TYPE["Worker Type<br/>🔧 Language compatibility"]  
 end  
   
 subgraph "⚖️ Scoring Algorithm"  
 RESOURCE\_SCORE["Resource Score<br/>💯 0-100 based on fit"]  
 LOCALITY\_SCORE["Locality Score<br/>💯 0-100 based on data"]  
 LOAD\_SCORE["Load Score<br/>💯 0-100 based on utilization"]  
 COMPOSITE\_SCORE["Composite Score<br/>🎯 Weighted combination"]  
 end  
   
 subgraph "🏆 Final Decision"  
 BEST\_WORKER["Best Worker<br/>👑 Highest scoring worker"]  
 FALLBACK["Fallback<br/>🔄 Alternative if first choice fails"]  
 QUEUING["Queuing<br/>⏳ Wait if no suitable worker"]  
 end  
   
 RESOURCE\_FIT --> RESOURCE\_SCORE  
 CURRENT\_LOAD --> LOAD\_SCORE  
 DATA\_LOCALITY --> LOCALITY\_SCORE  
 WORKER\_TYPE --> COMPOSITE\_SCORE  
   
 RESOURCE\_SCORE --> COMPOSITE\_SCORE  
 LOCALITY\_SCORE --> COMPOSITE\_SCORE  
 LOAD\_SCORE --> COMPOSITE\_SCORE  
   
 COMPOSITE\_SCORE --> BEST\_WORKER  
 BEST\_WORKER --> FALLBACK  
 FALLBACK --> QUEUING  
   
 style RESOURCE\_FIT fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style DATA\_LOCALITY fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style COMPOSITE\_SCORE fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style BEST\_WORKER fill:#c8e6c9,stroke:#2e7d32,stroke-width:2px,color:#000

## Task Execution Engine

### Worker Process Task Execution

Once a task is assigned to a worker, a sophisticated execution engine takes over:

sequenceDiagram  
 participant R as Raylet  
 participant W as Worker Process  
 participant TE as Task Executor  
 participant OS as Object Store  
 participant F as Function Runtime  
   
 R->>W: Assign task  
 W->>TE: Initialize task execution  
 TE->>OS: Resolve input dependencies  
 OS-->>TE: Return input objects  
 TE->>F: Execute user function  
 F->>F: Run Python code  
 F-->>TE: Return result  
 TE->>OS: Store result objects  
 TE->>W: Mark task complete  
 W->>R: Report task success  
   
 Note over R,F: Task execution with dependency resolution

Task Execution Implementation:

# From python/ray/\_private/worker.py (worker process)  
class TaskExecutor:  
 def execute\_task(self, task\_spec, task\_execution\_spec):  
 """Execute a single task in the worker process."""  
   
 # Step 1: Extract task information  
 function\_descriptor = task\_spec.function\_descriptor  
 args = task\_spec.args  
 task\_id = task\_spec.task\_id  
   
 # Step 2: Resolve function from registry  
 function = worker.function\_actor\_manager.get\_function(function\_descriptor)  
   
 # Step 3: Resolve input arguments  
 resolved\_args = []  
 for arg in args:  
 if arg.is\_by\_ref:  
 # Resolve ObjectRef to actual value  
 obj = ray.get(ObjectRef(arg.object\_ref.object\_id))  
 resolved\_args.append(obj)  
 else:  
 # Deserialize direct value  
 obj = ray.\_private.serialization.deserialize(arg.data)  
 resolved\_args.append(obj)  
   
 # Step 4: Execute the function  
 try:  
 with ray.\_private.profiling.profile\_task(task\_id):  
 result = function(\*resolved\_args)  
   
 # Step 5: Store result in object store  
 if isinstance(result, tuple):  
 # Multiple return values  
 return\_refs = []  
 for i, ret\_val in enumerate(result):  
 object\_id = ObjectID.from\_task\_and\_index(task\_id, i + 1)  
 ray.put(ret\_val, object\_id=object\_id)  
 return\_refs.append(object\_id)  
 return return\_refs  
 else:  
 # Single return value  
 object\_id = ObjectID.from\_task\_and\_index(task\_id, 1)  
 ray.put(result, object\_id=object\_id)  
 return [object\_id]  
   
 except Exception as e:  
 # Handle task execution error  
 error\_info = TaskExecutionError(e, traceback.format\_exc())  
 self.\_store\_task\_error(task\_id, error\_info)  
 raise

### Dependency Resolution System

Ray automatically resolves task dependencies before execution:

# Example: Complex dependency chain  
@ray.remote  
def load\_data(filename):  
 """Load data from file"""  
 import pandas as pd  
 return pd.read\_csv(filename)  
  
@ray.remote   
def preprocess\_data(data):  
 """Clean and prepare data"""  
 # Remove nulls, normalize, etc.  
 cleaned = data.dropna()  
 normalized = (cleaned - cleaned.mean()) / cleaned.std()  
 return normalized  
  
@ray.remote  
def train\_model(train\_data, test\_data):  
 """Train ML model"""  
 from sklearn.linear\_model import LinearRegression  
 model = LinearRegression()  
 model.fit(train\_data[['feature1', 'feature2']], train\_data['target'])  
 score = model.score(test\_data[['feature1', 'feature2']], test\_data['target'])  
 return {'model': model, 'score': score}  
  
@ray.remote  
def evaluate\_model(model\_data, validation\_data):  
 """Evaluate trained model"""  
 model = model\_data['model']  
 predictions = model.predict(validation\_data[['feature1', 'feature2']])  
 accuracy = calculate\_accuracy(predictions, validation\_data['target'])  
 return accuracy  
  
# Create dependency graph automatically  
raw\_train = load\_data.remote("train.csv") # Independent  
raw\_test = load\_data.remote("test.csv") # Independent   
raw\_val = load\_data.remote("validation.csv") # Independent  
  
clean\_train = preprocess\_data.remote(raw\_train) # Depends on raw\_train  
clean\_test = preprocess\_data.remote(raw\_test) # Depends on raw\_test  
clean\_val = preprocess\_data.remote(raw\_val) # Depends on raw\_val  
  
model\_result = train\_model.remote(clean\_train, clean\_test) # Depends on both  
  
final\_accuracy = evaluate\_model.remote(model\_result, clean\_val) # Depends on all  
  
# Ray automatically manages the entire dependency graph  
print(f"Final model accuracy: {ray.get(final\_accuracy)}")

## Task Dependencies and Lineage

### Dependency Graph Management

Ray maintains a sophisticated dependency graph for tasks:

graph TD  
 subgraph "📊 Data Sources"  
 FILE1["load\_data('train.csv')<br/>📄 Raw training data"]  
 FILE2["load\_data('test.csv')<br/>📄 Raw test data"]  
 FILE3["load\_data('validation.csv')<br/>📄 Raw validation data"]  
 end  
   
 subgraph "🧹 Preprocessing"  
 CLEAN1["preprocess\_data(train)<br/>🧹 Clean training data"]  
 CLEAN2["preprocess\_data(test)<br/>🧹 Clean test data"]  
 CLEAN3["preprocess\_data(val)<br/>🧹 Clean validation data"]  
 end  
   
 subgraph "🤖 Model Training"  
 TRAIN["train\_model(clean\_train, clean\_test)<br/>🤖 Trained model"]  
 end  
   
 subgraph "📊 Evaluation"  
 EVAL["evaluate\_model(model, clean\_val)<br/>📊 Final accuracy"]  
 end  
   
 FILE1 --> CLEAN1  
 FILE2 --> CLEAN2  
 FILE3 --> CLEAN3  
   
 CLEAN1 --> TRAIN  
 CLEAN2 --> TRAIN  
   
 TRAIN --> EVAL  
 CLEAN3 --> EVAL  
   
 style FILE1 fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style FILE2 fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style FILE3 fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style CLEAN1 fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style CLEAN2 fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style CLEAN3 fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style TRAIN fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style EVAL fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000

### Lineage Tracking and Fault Tolerance

Ray tracks the complete lineage of objects to enable fault tolerance:

// From src/ray/core\_worker/reference\_count.h  
class ReferenceCounter {  
 private:  
 // Maps object ID to its lineage information  
 absl::flat\_hash\_map<ObjectID, ObjectLineage> object\_lineage\_map\_;  
   
 // Maps object ID to the task that created it  
 absl::flat\_hash\_map<ObjectID, TaskID> object\_to\_task\_map\_;  
   
 public:  
 /// Add lineage information when object is created  
 void AddObjectLineage(const ObjectID &object\_id,  
 const TaskID &task\_id,  
 const std::vector<ObjectID> &dependencies) {  
 ObjectLineage lineage;  
 lineage.task\_id = task\_id;  
 lineage.dependencies = dependencies;  
 lineage.creation\_time = absl::Now();  
   
 object\_lineage\_map\_[object\_id] = lineage;  
 object\_to\_task\_map\_[object\_id] = task\_id;  
 }  
   
 /// Reconstruct object by re-executing its task  
 Status ReconstructObject(const ObjectID &object\_id) {  
 auto it = object\_lineage\_map\_.find(object\_id);  
 if (it == object\_lineage\_map\_.end()) {  
 return Status::NotFound("Object lineage not found");  
 }  
   
 const auto &lineage = it->second;  
   
 // First ensure all dependencies are available  
 for (const auto &dep\_id : lineage.dependencies) {  
 if (!IsObjectAvailable(dep\_id)) {  
 // Recursively reconstruct dependencies  
 auto status = ReconstructObject(dep\_id);  
 if (!status.ok()) {  
 return status;  
 }  
 }  
 }  
   
 // Re-execute the task that created this object  
 return ReExecuteTask(lineage.task\_id);  
 }  
};

This comprehensive guide covers the essential aspects of Ray's task system, from creation through execution to fault tolerance. Tasks form the foundation of Ray's distributed computing model, enabling scalable and fault-tolerant parallel computation.

Chapter 4: Part I: Ray Fundamentals

# Chapter 4: Actor Lifecycle and Management

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## Introduction

Ray actors are long-running, stateful workers that live somewhere in your cluster and can be called like remote objects. Think of an actor as a combination of a server process and a Python object - it has its own memory, state, and can handle multiple requests over time.

### What Makes Ray Actors Special?

Stateful Distributed Computing: Unlike functions that are stateless, actors maintain state between calls. Imagine having a database connection, machine learning model, or game state that persists across multiple operations.

Location Transparency: You interact with actors using handles that look like regular Python objects, even though the actor might be running on a machine thousands of miles away.

### Core Actor Concepts

graph TB  
 subgraph "🎭 Actor Lifecycle"  
 CREATION["Actor Creation<br/>🏗️ Spawn new process"]  
 INITIALIZATION["Initialization<br/>🚀 Run \_\_init\_\_ method"]  
 READY["Ready State<br/>✅ Accept method calls"]  
 EXECUTION["Method Execution<br/>⚡ Process requests"]  
 TERMINATION["Termination<br/>💀 Cleanup and exit"]  
 end  
   
 CREATION --> INITIALIZATION  
 INITIALIZATION --> READY  
 READY --> EXECUTION  
 EXECUTION --> READY  
 EXECUTION --> TERMINATION  
   
 style CREATION fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style READY fill:#e8f5e8,stroke:#1b5e20,stroke-width:3px,color:#000

## Actor Architecture Overview

### High-Level Actor System Architecture

Ray's actor system is built on several layers that work together to provide the illusion of stateful, distributed objects:

graph TB  
 subgraph "🎯 User Level"  
 ACTOR\_CLASS["@ray.remote Actor Class<br/>📝 User-defined behavior"]  
 ACTOR\_HANDLE["Actor Handle<br/>🎭 Remote object reference"]  
 METHOD\_CALLS["Method Calls<br/>📞 actor.method.remote()"]  
 end  
   
 subgraph "🧠 Core Worker Layer"  
 ACTOR\_MGR["Actor Manager<br/>🎭 Lifecycle coordination"]  
 TASK\_SUBMITTER["Task Submitter<br/>📋 Method dispatching"]  
 REF\_COUNTER["Reference Counter<br/>🔢 Garbage collection"]  
 end  
   
 subgraph "🌐 Cluster Services"  
 GCS\_ACTOR\_MGR["GCS Actor Manager<br/>🏛️ Global state"]  
 ACTOR\_SCHEDULER["Actor Scheduler<br/>⚖️ Placement decisions"]  
 RAYLET\_MGR["Raylet Manager<br/>🔧 Local execution"]  
 end  
   
 ACTOR\_CLASS --> ACTOR\_MGR  
 ACTOR\_HANDLE --> TASK\_SUBMITTER  
 METHOD\_CALLS --> REF\_COUNTER  
   
 ACTOR\_MGR --> GCS\_ACTOR\_MGR  
 TASK\_SUBMITTER --> ACTOR\_SCHEDULER  
 REF\_COUNTER --> RAYLET\_MGR  
   
 style ACTOR\_CLASS fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style ACTOR\_HANDLE fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style ACTOR\_MGR fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000

## Actor Creation Deep Dive

### Phase 1: Actor Definition and Registration

When you define an actor class, Ray prepares it for distributed execution:

# User code  
@ray.remote(num\_cpus=2, num\_gpus=1)  
class GameServer:  
 def \_\_init\_\_(self, max\_players=100):  
 self.players = {}  
 self.max\_players = max\_players  
 self.game\_state = "waiting"  
   
 def add\_player(self, player\_id, player\_data):  
 if len(self.players) < self.max\_players:  
 self.players[player\_id] = player\_data  
 return True  
 return False  
  
# Create actor instance  
game\_server = GameServer.remote(max\_players=50)

Behind the Scenes - Class Registration:

# From python/ray/\_private/worker.py  
def make\_actor(cls, num\_cpus, num\_gpus, memory, \*\*kwargs):  
 """Convert a regular class into a Ray actor class."""  
   
 # Step 1: Create actor class metadata  
 class\_id = compute\_class\_id(cls)  
   
 # Step 2: Register class with driver's core worker  
 driver\_worker = ray.\_private.worker.global\_worker  
 driver\_worker.function\_actor\_manager.export\_actor\_class(  
 cls, class\_id, num\_cpus, num\_gpus, memory)  
   
 # Step 3: Create actor handle factory  
 def remote(\*args, \*\*kwargs):  
 return ActorHandle.\_remote(args=args, kwargs=kwargs)  
   
 # Step 4: Return modified class with remote() method  
 cls.remote = remote  
 return cls

### Phase 2: Actor Instance Creation

When you call ClassName.remote(), a complex creation process begins:

sequenceDiagram  
 participant U as User Code  
 participant API as Ray API  
 participant CW as CoreWorker  
 participant GCS as GCS Server  
 participant R as Raylet  
 participant AW as Actor Worker  
   
 U->>API: GameServer.remote(max\_players=50)  
 API->>CW: Create actor request  
 CW->>GCS: Submit actor creation task  
 GCS->>R: Assign actor to node  
 R->>AW: Start actor worker process  
 AW->>AW: Initialize actor instance  
 AW->>GCS: Register actor as ready  
 GCS->>CW: Return actor handle  
 CW->>API: Return ActorHandle  
 API->>U: Return game\_server handle

Detailed Actor Creation Code:

// From src/ray/core\_worker/core\_worker.cc  
Status CoreWorker::CreateActor(const RayFunction &function,  
 const std::vector<std::unique\_ptr<TaskArg>> &args,  
 const ActorCreationOptions &actor\_creation\_options,  
 std::vector<rpc::ObjectReference> \*returned\_refs) {  
   
 // Step 1: Generate unique actor ID   
 const ActorID actor\_id = ActorID::FromRandom();  
   
 // Step 2: Build actor creation task spec  
 TaskSpecBuilder builder;  
 builder.SetActorCreationTask(  
 actor\_id, function, args,  
 actor\_creation\_options.max\_restarts,  
 actor\_creation\_options.resources);  
   
 const TaskSpec task\_spec = builder.Build();  
   
 // Step 3: Register with actor manager for tracking  
 actor\_manager\_->RegisterActorHandle(actor\_id, task\_spec);  
   
 // Step 4: Submit to GCS for global scheduling  
 return gcs\_client\_->actor\_accessor\_->AsyncCreateActor(task\_spec);  
}

## Method Invocation and Execution

### Method Call Flow

When you call a method on an actor handle, a sophisticated routing and execution process occurs:

sequenceDiagram  
 participant C as Client Code  
 participant H as Actor Handle  
 participant CW as CoreWorker  
 participant R as Raylet  
 participant AW as Actor Worker  
 participant A as Actor Instance  
   
 C->>H: game\_server.add\_player.remote(id, data)  
 H->>CW: Submit actor task  
 CW->>R: Route to actor's raylet  
 R->>AW: Forward method call  
 AW->>A: Invoke add\_player(id, data)  
 A->>A: Execute method logic  
 A-->>AW: Return result  
 AW-->>R: Send result  
 R-->>CW: Return object reference  
 CW-->>H: Return ObjectRef  
 H-->>C: Return future result

### Method Execution Engine

Inside the actor worker, methods are executed by a specialized runtime:

# From python/ray/\_private/worker.py (actor worker execution)  
class ActorMethodExecutor:  
 def \_\_init\_\_(self, actor\_instance):  
 self.actor\_instance = actor\_instance  
 self.method\_queue = queue.Queue()  
   
 def \_execute\_methods(self):  
 """Main execution loop for actor methods"""  
 while True:  
 try:  
 # Get next method call  
 method\_call = self.method\_queue.get()  
   
 if method\_call is None: # Shutdown signal  
 break  
   
 # Extract method info  
 method\_name = method\_call.function\_name  
 args = method\_call.args  
 kwargs = method\_call.kwargs  
   
 # Execute method on actor instance  
 method = getattr(self.actor\_instance, method\_name)  
 result = method(\*args, \*\*kwargs)  
   
 # Store result in object store  
 self.\_store\_result(method\_call.task\_id, result)  
   
 except Exception as e:  
 # Handle method execution error  
 self.\_store\_error(method\_call.task\_id, e)

## Fault Tolerance and Recovery

### Actor Restart Policies

Ray provides sophisticated fault tolerance mechanisms for actors:

# Different restart policies  
@ray.remote(max\_restarts=3, max\_task\_retries=2)  
class FaultTolerantActor:  
 def \_\_init\_\_(self):  
 self.state = {"counter": 0, "last\_update": time.time()}  
   
 def increment(self):  
 self.state["counter"] += 1  
 self.state["last\_update"] = time.time()  
   
 # Simulate occasional failures  
 if random.random() < 0.1:  
 raise Exception("Simulated failure")  
   
 return self.state["counter"]

### Failure Detection and Recovery

sequenceDiagram  
 participant C as Client  
 participant H as Actor Handle  
 participant GCS as GCS Server  
 participant HM as Health Monitor  
 participant R as Raylet  
 participant AW as Actor Worker  
   
 Note over C,AW: Normal Operation  
 C->>H: Method call  
 H->>AW: Execute method  
 AW-->>H: Return result  
   
 Note over C,AW: Failure Detection  
 HM->>AW: Health check  
 AW->>AW: ❌ Process crash  
 HM->>GCS: Report actor death  
 GCS->>GCS: Check restart policy  
   
 Note over C,AW: Recovery Process  
 GCS->>R: Start new actor instance  
 R->>AW: Launch new worker  
 AW->>GCS: Register as ready  
   
 Note over C,AW: Resume Operation  
 C->>H: Retry method call  
 H->>AW: Execute on new instance  
 AW-->>H: Return result

This comprehensive guide covers the fundamental aspects of Ray's actor system. Actors provide a powerful abstraction for building stateful, distributed applications with strong consistency guarantees and fault tolerance features.

Chapter 5: Part I: Ray Fundamentals

# Chapter 5: Memory and Object Reference System

## Introduction

Ray's memory and object reference system is like having a distributed, shared memory across your entire cluster. Instead of copying data between machines, Ray creates smart "pointers" (ObjectRefs) that can reference data stored anywhere in the cluster. This enables efficient sharing of large datasets and computation results.

### What Makes Ray's Memory System Special?

Zero-Copy Data Sharing: Large objects are stored once and referenced many times without copying.

Automatic Garbage Collection: Objects are cleaned up automatically when no longer needed.

Location Transparency: Your code doesn't need to know where data is physically stored.

Fault Tolerance: Objects can be reconstructed if they're lost due to node failures.

## Architecture Overview

graph TB  
 subgraph "🎯 User Interface"  
 OBJECT\_REF["ObjectRef<br/>🏷️ Smart pointer to data"]  
 RAY\_GET["ray.get()<br/>📥 Retrieve object value"]  
 RAY\_PUT["ray.put()<br/>📤 Store object in cluster"]  
 end  
   
 subgraph "🧠 Reference Management"  
 REF\_COUNTER["Reference Counter<br/>🔢 Track object usage"]  
 OWNERSHIP["Ownership Tracking<br/>👤 Who owns what"]  
 LINEAGE["Lineage Tracking<br/>🔗 How objects were created"]  
 end  
   
 subgraph "💾 Distributed Storage"  
 OBJECT\_STORE\_1["Object Store 1<br/>💿 Node A storage"]  
 OBJECT\_STORE\_2["Object Store 2<br/>💿 Node B storage"]  
 OBJECT\_STORE\_3["Object Store 3<br/>💿 Node C storage"]  
 end  
   
 subgraph "🏛️ Global Coordination"  
 GCS\_OBJECT\_MGR["GCS Object Manager<br/>🗂️ Global object directory"]  
 LOCATION\_SERVICE["Location Service<br/>📍 Where is each object?"]  
 end  
   
 OBJECT\_REF --> REF\_COUNTER  
 RAY\_GET --> OWNERSHIP  
 RAY\_PUT --> LINEAGE  
   
 REF\_COUNTER --> GCS\_OBJECT\_MGR  
 OWNERSHIP --> LOCATION\_SERVICE  
 LINEAGE --> OBJECT\_STORE\_1  
   
 GCS\_OBJECT\_MGR --> OBJECT\_STORE\_1  
 LOCATION\_SERVICE --> OBJECT\_STORE\_2  
 OBJECT\_STORE\_1 --> OBJECT\_STORE\_3  
   
 style OBJECT\_REF fill:#e1f5fe,stroke:#01579b,stroke-width:3px,color:#000  
 style REF\_COUNTER fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style OBJECT\_STORE\_1 fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style GCS\_OBJECT\_MGR fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000

## Object References (ObjectRefs)

### What is an ObjectRef?

An ObjectRef is like a "smart pointer" that references data stored somewhere in your Ray cluster:

import ray  
import numpy as np  
  
# Create a large dataset  
large\_array = np.random.random((1000000, 100))  
  
# Store in Ray's distributed object store  
object\_ref = ray.put(large\_array)  
print(f"ObjectRef: {object\_ref}")  
# Output: ObjectRef(c8ef45ccd0112571ffffffffffffffffffffffff01000000)  
  
# The actual data is stored in the cluster, not in this variable  
print(f"ObjectRef size in memory: {sys.getsizeof(object\_ref)} bytes")  
# Output: ObjectRef size in memory: 56 bytes (just the reference!)  
  
# Retrieve the data when needed  
retrieved\_array = ray.get(object\_ref)  
print(f"Retrieved array shape: {retrieved\_array.shape}")  
# Output: Retrieved array shape: (1000000, 100)

### ObjectRef Lifecycle

sequenceDiagram  
 participant U as User Code  
 participant CW as CoreWorker  
 participant OS as Object Store  
 participant GCS as GCS  
 participant RC as Reference Counter  
   
 U->>CW: ray.put(large\_data)  
 CW->>OS: Store object  
 OS-->>CW: Return ObjectID  
 CW->>GCS: Register object metadata  
 CW->>RC: Add reference count  
 CW-->>U: Return ObjectRef  
   
 Note over U,RC: Object is now stored and tracked  
   
 U->>CW: ray.get(object\_ref)  
 CW->>OS: Retrieve object  
 OS-->>CW: Return object data  
 CW-->>U: Return actual data  
   
 Note over U,RC: When ObjectRef goes out of scope...  
   
 U->>RC: Reference deleted  
 RC->>RC: Decrement count  
 RC->>GCS: Count reached zero  
 GCS->>OS: Delete object

### Automatic Object Creation

Objects are automatically stored when returned from remote functions:

@ray.remote  
def create\_large\_dataset():  
 # This creates a large object  
 return np.random.random((100000, 1000))  
  
@ray.remote  
def process\_dataset(data):  
 # Process the data  
 return np.mean(data, axis=0)  
  
# Object is automatically stored in object store  
dataset\_ref = create\_large\_dataset.remote() # Returns ObjectRef immediately  
  
# Pass ObjectRef to another task (no data copying!)  
result\_ref = process\_dataset.remote(dataset\_ref)  
  
# Only retrieve when final result is needed  
final\_result = ray.get(result\_ref)

## Distributed Object Store

### Plasma Object Store

Ray uses Apache Plasma for high-performance object storage:

// From src/ray/object\_store/plasma/client.h  
class PlasmaClient {  
 public:  
 /// Store an object in the plasma store  
 Status Put(const ObjectID &object\_id,  
 const uint8\_t \*data,  
 size\_t data\_size,  
 const uint8\_t \*metadata = nullptr,  
 size\_t metadata\_size = 0) {  
   
 // Step 1: Create plasma object buffer  
 std::shared\_ptr<Buffer> buffer;  
 Status create\_status = Create(object\_id, data\_size, &buffer);  
 if (!create\_status.ok()) {  
 return create\_status;  
 }  
   
 // Step 2: Copy data into shared memory  
 std::memcpy(buffer->mutable\_data(), data, data\_size);  
   
 // Step 3: Seal object (make it immutable and available)  
 return Seal(object\_id);  
 }  
   
 /// Get objects from the plasma store  
 Status Get(const std::vector<ObjectID> &object\_ids,  
 int64\_t timeout\_ms,  
 std::vector<ObjectBuffer> \*object\_buffers) {  
   
 // Wait for objects to become available  
 return impl\_->Wait(object\_ids, timeout\_ms, object\_buffers);  
 }  
};

### Multi-Node Object Access

graph TB  
 subgraph "🖥️ Node A"  
 TASK\_A["Task A<br/>Creates large\_data"]  
 STORE\_A["Object Store A<br/>💿 Stores large\_data"]  
 end  
   
 subgraph "🖥️ Node B"  
 TASK\_B["Task B<br/>Needs large\_data"]  
 STORE\_B["Object Store B<br/>💿 Local cache"]  
 end  
   
 subgraph "🖥️ Node C"   
 TASK\_C["Task C<br/>Also needs large\_data"]  
 STORE\_C["Object Store C<br/>💿 Local cache"]  
 end  
   
 subgraph "🏛️ Global Directory"  
 GCS\_DIR["GCS Object Directory<br/>📍 Tracks object locations"]  
 end  
   
 TASK\_A --> STORE\_A  
 STORE\_A --> GCS\_DIR  
   
 TASK\_B --> GCS\_DIR  
 GCS\_DIR --> STORE\_A  
 STORE\_A --> STORE\_B  
 STORE\_B --> TASK\_B  
   
 TASK\_C --> STORE\_B  
 STORE\_B --> STORE\_C  
 STORE\_C --> TASK\_C  
   
 style TASK\_A fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style STORE\_A fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style GCS\_DIR fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style STORE\_B fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000

## Memory Management Patterns

### Efficient Data Sharing

# Example: Sharing large datasets efficiently  
@ray.remote  
def load\_model():  
 """Load a large ML model once"""  
 import joblib  
 model = joblib.load('large\_model.pkl') # 2GB model  
 return model  
  
@ray.remote   
def predict\_batch(model\_ref, data\_batch):  
 """Use shared model for prediction"""  
 model = ray.get(model\_ref) # Gets reference, not copy  
 return model.predict(data\_batch)  
  
# Load model once, share across many tasks  
model\_ref = load\_model.remote()  
  
# All tasks share the same model (no copying!)  
predictions = []  
for batch in data\_batches:  
 pred\_ref = predict\_batch.remote(model\_ref, batch)  
 predictions.append(pred\_ref)  
  
results = ray.get(predictions)

### Memory-Efficient Processing

# Memory-efficient processing of large datasets  
@ray.remote  
def process\_chunk(data\_chunk):  
 """Process a chunk of data"""  
 # Process data and return smaller result  
 processed = expensive\_computation(data\_chunk)  
 return summarize(processed) # Return summary, not full data  
  
# Split large dataset into chunks  
large\_dataset = load\_huge\_dataset() # 100GB dataset  
chunk\_size = len(large\_dataset) // num\_workers  
  
chunk\_refs = []  
for i in range(0, len(large\_dataset), chunk\_size):  
 chunk = large\_dataset[i:i + chunk\_size]  
 chunk\_ref = ray.put(chunk) # Store chunk in object store  
 chunk\_refs.append(chunk\_ref)  
  
# Process chunks in parallel  
result\_refs = [process\_chunk.remote(chunk\_ref) for chunk\_ref in chunk\_refs]  
  
# Combine results (much smaller than original data)  
results = ray.get(result\_refs)  
final\_result = combine\_results(results)

## Reference Counting and Garbage Collection

### Automatic Cleanup

Ray automatically cleans up objects when they're no longer needed:

// From src/ray/core\_worker/reference\_count.h  
class ReferenceCounter {  
 private:  
 // Track reference counts for each object  
 absl::flat\_hash\_map<ObjectID, int> object\_ref\_counts\_;  
   
 // Track which worker owns each object  
 absl::flat\_hash\_map<ObjectID, WorkerID> object\_owners\_;  
   
 public:  
 /// Add a reference to an object  
 void AddObjectRef(const ObjectID &object\_id, const WorkerID &owner\_id) {  
 object\_ref\_counts\_[object\_id]++;  
 object\_owners\_[object\_id] = owner\_id;  
 }  
   
 /// Remove a reference to an object  
 void RemoveObjectRef(const ObjectID &object\_id) {  
 auto it = object\_ref\_counts\_.find(object\_id);  
 if (it != object\_ref\_counts\_.end()) {  
 it->second--;  
   
 if (it->second == 0) {  
 // No more references - schedule for deletion  
 ScheduleObjectDeletion(object\_id);  
 object\_ref\_counts\_.erase(it);  
 object\_owners\_.erase(object\_id);  
 }  
 }  
 }  
   
 private:  
 void ScheduleObjectDeletion(const ObjectID &object\_id) {  
 // Send deletion request to object store  
 deletion\_queue\_.push(object\_id);  
 }  
};

### Manual Memory Management

You can also manually control object lifecycle:

import ray  
  
# Create object  
data = ray.put(large\_dataset)  
  
# Use object  
result = process\_data.remote(data)  
final\_result = ray.get(result)  
  
# Manually delete when done (optional - Ray will do this automatically)  
del data # Remove reference  
ray.internal.free([data]) # Force cleanup

## Object Reconstruction and Fault Tolerance

### Lineage-Based Recovery

Ray can reconstruct lost objects using lineage information:

# Example: Fault-tolerant computation chain  
@ray.remote  
def step1():  
 return expensive\_computation\_1()  
  
@ray.remote   
def step2(data1):  
 return expensive\_computation\_2(data1)  
  
@ray.remote  
def step3(data2):  
 return expensive\_computation\_3(data2)  
  
# Build computation chain  
result1 = step1.remote()  
result2 = step2.remote(result1)   
result3 = step3.remote(result2)  
  
# If any intermediate result is lost due to node failure,  
# Ray can reconstruct it by re-running the necessary tasks  
final\_result = ray.get(result3) # Handles reconstruction transparently

### Reconstruction Process

sequenceDiagram  
 participant App as Application  
 participant GCS as GCS  
 participant Node1 as Node 1 (Failed)  
 participant Node2 as Node 2  
 participant RC as Reconstructor  
   
 App->>GCS: ray.get(lost\_object\_ref)  
 GCS->>GCS: Object not found in cluster  
 GCS->>RC: Reconstruct object using lineage  
 RC->>Node2: Re-run task that created object  
 Node2->>Node2: Execute task  
 Node2->>GCS: Store reconstructed object  
 GCS-->>App: Return reconstructed object  
   
 Note over App,RC: Transparent reconstruction

## Performance Optimization

### Object Store Memory Management

# Configure object store memory  
ray.init(object\_store\_memory=8\_000\_000\_000) # 8GB for object store  
  
# Monitor object store usage  
print(ray.cluster\_resources())  
# Output: {'CPU': 8.0, 'memory': 16000000000, 'object\_store\_memory': 8000000000}  
  
# Check current object store usage  
import psutil  
object\_store\_memory = ray.\_private.utils.get\_system\_memory() // 2  
print(f"Object store memory limit: {object\_store\_memory / 1e9:.1f} GB")

### Best Practices

# 1. Use ray.put() for large objects used multiple times  
large\_model = load\_model()  
model\_ref = ray.put(large\_model) # Store once  
  
# Use reference in multiple tasks  
results = [predict.remote(model\_ref, batch) for batch in batches]  
  
# 2. Return smaller objects from tasks  
@ray.remote  
def process\_large\_data(big\_data\_ref):  
 big\_data = ray.get(big\_data\_ref)  
 result = expensive\_processing(big\_data)  
 return summarize(result) # Return summary, not full result  
  
# 3. Use object references for intermediate results  
@ray.remote  
def pipeline\_step1(data):  
 return process\_step1(data)  
  
@ray.remote   
def pipeline\_step2(step1\_result\_ref):  
 # Pass reference, not actual data  
 step1\_result = ray.get(step1\_result\_ref)  
 return process\_step2(step1\_result)

This comprehensive guide covers Ray's sophisticated memory management system that enables efficient distributed computing with automatic garbage collection and fault tolerance.

Chapter 6: Part II: Core Ray Services

# Chapter 6: Global Control Service (GCS)

# Ray GCS Server: Comprehensive Technical Guide

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## Introduction

The GCS (Global Control Service) server is the central coordination hub of a Ray cluster. It maintains authoritative global state about all cluster resources, nodes, actors, jobs, and placement groups. The GCS serves as the single source of truth for cluster-wide metadata and coordinates distributed operations across the entire Ray cluster.

### Key Responsibilities

1. Node Registration and Health Monitoring: Track all nodes joining/leaving the cluster 2. Resource Management: Coordinate cluster-wide resource allocation and scheduling 3. Actor Management: Handle actor creation, placement, and lifecycle 4. Job Coordination: Manage job submission, tracking, and cleanup 5. Metadata Storage: Persist critical cluster state and configuration 6. Service Discovery: Provide endpoints for cluster services

## Architecture Overview

graph TB  
 subgraph "Ray Cluster Architecture"  
 subgraph "GCS Server (Head Node)"  
 subgraph "Core Managers"  
 NodeMgr["Node Manager<br/>Node lifecycle & health"]  
 ResourceMgr["Resource Manager<br/>Cluster resources"]  
 ActorMgr["Actor Manager<br/>Actor coordination"]  
 JobMgr["Job Manager<br/>Job lifecycle"]  
 PlacementMgr["Placement Group Manager<br/>Group scheduling"]  
 end  
   
 subgraph "Infrastructure"  
 Storage["Table Storage<br/>Redis/Memory"]  
 PubSub["Pub/Sub System<br/>Event distribution"]  
 RPC["gRPC Server<br/>Client communication"]  
 KVStore["KV Manager<br/>Configuration store"]  
 end  
 end  
   
 subgraph "Worker Nodes"  
 subgraph "Raylet 1"  
 RM1["Resource Manager"]  
 NM1["Node Manager"]  
 end  
 subgraph "Raylet 2"  
 RM2["Resource Manager"]  
 NM2["Node Manager"]  
 end  
 end  
   
 subgraph "External Systems"  
 Redis[(Redis Storage)]  
 Clients["Ray Clients<br/>Drivers & SDKs"]  
 Monitoring["Monitoring<br/>Prometheus/etc"]  
 end  
 end  
   
 NodeMgr <--> RM1  
 NodeMgr <--> RM2  
   
 ResourceMgr <--> RM1  
 ResourceMgr <--> RM2  
   
 ActorMgr <--> NM1  
 ActorMgr <--> NM2  
   
 Storage <--> Redis  
 PubSub <--> Storage  
   
 RPC <--> Clients  
 RPC <--> Monitoring  
   
 NodeMgr <--> Storage  
 ResourceMgr <--> Storage  
 ActorMgr <--> Storage  
 JobMgr <--> Storage  
   
 style NodeMgr fill:#e1f5fe  
 style ResourceMgr fill:#f3e5f5  
 style Storage fill:#e8f5e8  
 style RPC fill:#fff3e0

### GCS Server Design Principles

1. Single Source of Truth: All authoritative cluster state lives in GCS 2. Event-Driven Architecture: State changes trigger cascading updates 3. Scalable Storage: Pluggable backend storage (Redis, Memory) 4. Fault Recovery: Persistent state enables cluster recovery 5. Performance Optimization: Caching and batching for high throughput

## Core Components

The GCS server consists of several specialized managers working together:

### Component Initialization Order

From src/ray/gcs/gcs\_server/gcs\_server.h:140-180:

sequenceDiagram  
 participant Main as Main Process  
 participant GCS as GCS Server  
 participant Storage as Table Storage  
 participant Managers as Component Managers  
   
 Note over Main,Managers: GCS Server Startup Flow  
   
 Main->>GCS: Create GcsServer(config)  
 GCS->>Storage: Initialize storage backend  
 Storage->>Storage: Connect to Redis/Memory  
   
 GCS->>GCS: InitGcsNodeManager()  
 GCS->>GCS: InitGcsResourceManager()  
 GCS->>GCS: InitGcsJobManager()  
 GCS->>GCS: InitGcsActorManager()  
 GCS->>GCS: InitGcsPlacementGroupManager()  
 GCS->>GCS: InitGcsWorkerManager()  
 GCS->>GCS: InitGcsTaskManager()  
   
 GCS->>GCS: InitKVManager()  
 GCS->>GCS: InitPubSubHandler()  
 GCS->>GCS: InitRuntimeEnvManager()  
   
 GCS->>Managers: Install event listeners  
 GCS->>Main: Start RPC server  
   
 Note over Main,Managers: Ready to handle requests

### GCS Server Configuration

From src/ray/gcs/gcs\_server/gcs\_server.h:47-62:

struct GcsServerConfig {  
 std::string grpc\_server\_name = "GcsServer";  
 uint16\_t grpc\_server\_port = 0; // GCS RPC port  
 uint16\_t grpc\_server\_thread\_num = 1; // RPC thread pool size  
 std::string redis\_username; // Redis authentication  
 std::string redis\_password;  
 std::string redis\_address; // Redis host address   
 uint16\_t redis\_port = 6379; // Redis port  
 bool enable\_redis\_ssl = false; // TLS encryption  
 bool retry\_redis = true; // Connection retry logic  
 bool enable\_sharding\_conn = false; // Redis sharding  
 std::string node\_ip\_address; // GCS server IP  
 std::string log\_dir; // Logging directory  
 std::string raylet\_config\_list; // Raylet configurations  
 std::string session\_name; // Cluster session ID  
};

## Node Lifecycle Management

The GCS Node Manager is responsible for tracking all nodes in the cluster and their health status.

### Node State Machine

stateDiagram-v2  
 [\*] --> Registering: Node startup  
 Registering --> Alive: Registration successful  
   
 Alive --> Draining: Graceful shutdown request  
 Alive --> Dead: Node failure detected  
   
 Draining --> Dead: Drain timeout/completion  
   
 Dead --> [\*]: Node cleanup complete  
   
 note right of Alive  
 Node actively participating  
 in cluster operations  
 end note  
   
 note right of Draining  
 Node preparing for shutdown,  
 tasks being migrated  
 end note  
   
 note right of Dead  
 Node removed from cluster,  
 resources deallocated  
 end note

### Node Registration Protocol

From src/ray/gcs/gcs\_server/gcs\_node\_manager.h:54-62:

sequenceDiagram  
 participant Raylet as Raylet Process  
 participant GCS as GCS Node Manager  
 participant Storage as Table Storage  
 participant PubSub as Pub/Sub System  
   
 Note over Raylet,PubSub: Node Registration Flow  
   
 Raylet->>GCS: RegisterNode(node\_info, resources)  
 GCS->>GCS: Validate node information  
 GCS->>Storage: Store node in alive\_nodes table  
 Storage-->>GCS: Storage confirmation  
   
 GCS->>PubSub: Publish NODE\_ADDED event  
 PubSub->>PubSub: Notify subscribers  
   
 GCS->>GCS: Trigger node\_added\_listeners  
 GCS->>Raylet: RegisterNodeReply(success)  
   
 Note over Raylet,PubSub: Node now active in cluster

Node Information Structure:

// From gcs.proto - rpc::GcsNodeInfo  
message GcsNodeInfo {  
 bytes node\_id = 1; // Unique node identifier  
 string node\_manager\_address = 2; // Node IP address  
 int32 node\_manager\_port = 3; // Node manager port  
 int32 object\_manager\_port = 4; // Object manager port  
 string node\_name = 5; // Human-readable name  
 map<string, double> resources\_total = 6; // Total node resources  
 GcsNodeState state = 7; // Current node state  
 NodeDeathInfo death\_info = 8; // Death information if dead  
 int64 start\_time\_ms = 9; // Node startup timestamp  
}  
  
enum GcsNodeState {  
 ALIVE = 0; // Node operational  
 DEAD = 1; // Node failed/removed  
 DRAINING = 2; // Node shutting down gracefully  
}

### Health Monitoring and Failure Detection

Health Check Mechanisms:

1. Periodic Heartbeats: Raylets send regular health updates 2. Resource Reports: Nodes report resource usage changes 3. Task Status Updates: Monitor task execution health 4. Network Connectivity: Detect network partitions

graph LR  
 subgraph "Health Monitoring System"  
 subgraph "Detection Methods"  
 Heartbeat["Periodic Heartbeats<br/>30s intervals"]  
 ResourceReport["Resource Reports<br/>Real-time updates"]  
 TaskStatus["Task Status<br/>Execution monitoring"]  
 Network["Network Checks<br/>Connection monitoring"]  
 end  
   
 subgraph "Failure Response"  
 Detection["Failure Detection"]  
 Cleanup["Resource Cleanup"]  
 Redistribution["Task Redistribution"]  
 Notification["Event Notification"]  
 end  
 end  
   
 Heartbeat --> Detection  
 ResourceReport --> Detection  
 TaskStatus --> Detection  
 Network --> Detection  
   
 Detection --> Cleanup  
 Detection --> Redistribution  
 Detection --> Notification  
   
 style Detection fill:#ff9999  
 style Cleanup fill:#ffcc99  
 style Redistribution fill:#99ccff  
 style Notification fill:#99ff99

## Resource Management

The GCS Resource Manager maintains a global view of all cluster resources and coordinates scheduling decisions.

### Resource Architecture

graph TB  
 subgraph "Resource Management Hierarchy"  
 subgraph "Global Level (GCS)"  
 GlobalView["Global Resource View<br/>Cluster-wide aggregation"]  
 Scheduler["Cluster Resource Scheduler<br/>Global scheduling decisions"]  
 Policy["Scheduling Policies<br/>Placement strategies"]  
 end  
   
 subgraph "Node Level (Raylet)"  
 NodeResources["Node Resource Manager<br/>Local resource tracking"]  
 LocalScheduler["Local Task Manager<br/>Local scheduling"]  
 Workers["Worker Pool<br/>Process management"]  
 end  
   
 subgraph "Task Level"  
 TaskRequests["Task Resource Requests<br/>CPU, GPU, memory"]  
 PlacementGroups["Placement Groups<br/>Co-location constraints"]  
 Reservations["Resource Reservations<br/>Temporary allocations"]  
 end  
 end  
   
 GlobalView <--> NodeResources  
 Scheduler <--> LocalScheduler  
 Policy <--> PlacementGroups  
   
 NodeResources <--> Workers  
 LocalScheduler <--> TaskRequests  
 Reservations <--> Workers  
   
 style GlobalView fill:#e1f5fe  
 style Scheduler fill:#f3e5f5  
 style NodeResources fill:#e8f5e8  
 style TaskRequests fill:#fff3e0

### Resource Types and Management

Core Resource Types:

// Resource categories managed by GCS  
enum ResourceType {  
 CPU, // Compute cores  
 GPU, // Graphics processors   
 MEMORY, // RAM allocation  
 OBJECT\_STORE\_MEMORY, // Plasma store memory  
 CUSTOM // User-defined resources  
};  
  
// Resource scheduling information  
struct ResourceSchedulingState {  
 map<string, double> total; // Total available resources  
 map<string, double> available; // Currently available resources  
 map<string, double> used; // Currently used resources  
 vector<TaskSpec> pending\_tasks; // Tasks waiting for resources  
};

### Resource Synchronization Protocol

sequenceDiagram  
 participant Node as Raylet Node  
 participant GCS as GCS Resource Manager  
 participant Scheduler as Cluster Scheduler  
 participant Client as Task Submitter  
   
 Note over Node,Client: Resource Update Flow  
   
 Node->>GCS: UpdateResources(current\_usage)  
 GCS->>GCS: Update global resource view  
 GCS->>Scheduler: Notify resource changes  
   
 Client->>GCS: SubmitTask(resource\_requirements)  
 GCS->>Scheduler: FindNodeForTask(requirements)  
 Scheduler->>Scheduler: Evaluate placement options  
 Scheduler->>GCS: NodeAssignment(node\_id)  
   
 GCS->>Node: ScheduleTask(task\_spec)  
 Node->>Node: Reserve resources locally  
 Node->>GCS: ResourceReservationConfirm()  
   
 Note over Node,Client: Task execution begins

## Actor Management

The GCS Actor Manager handles the distributed coordination of Ray actors, including creation, placement, and lifecycle management.

### Actor Lifecycle Management

stateDiagram-v2  
 [\*] --> Pending: Actor creation request  
 Pending --> Alive: Actor successfully started  
 Pending --> Failed: Creation failed  
   
 Alive --> Restarting: Actor failure (restartable)  
 Alive --> Dead: Actor termination  
   
 Restarting --> Alive: Restart successful  
 Restarting --> Dead: Restart failed/max attempts  
   
 Failed --> [\*]: Creation cleanup  
 Dead --> [\*]: Actor cleanup complete  
   
 note right of Pending  
 Waiting for resource allocation  
 and worker assignment  
 end note  
   
 note right of Alive  
 Actor processing tasks,  
 state maintained  
 end note  
   
 note right of Restarting  
 Actor failed but configured  
 for automatic restart  
 end note

### Actor Creation Protocol

sequenceDiagram  
 participant Client as Ray Client  
 participant GCS as GCS Actor Manager  
 participant Scheduler as Resource Scheduler  
 participant Node as Target Raylet  
 participant Worker as Actor Worker  
   
 Note over Client,Worker: Actor Creation Flow  
   
 Client->>GCS: CreateActor(actor\_spec, placement\_options)  
 GCS->>GCS: Generate unique ActorID  
 GCS->>Scheduler: RequestWorkerLease(resource\_requirements)  
   
 Scheduler->>Node: GrantWorkerLease(lease\_info)  
 Node->>Worker: StartWorker(actor\_spec)  
 Worker->>Worker: Initialize actor state  
   
 Worker->>Node: ActorCreationComplete(actor\_id)  
 Node->>GCS: ReportActorCreation(actor\_id, worker\_info)  
 GCS->>GCS: Update actor registry  
 GCS->>Client: CreateActorReply(actor\_handle)  
   
 Note over Client,Worker: Actor ready for method calls

### Actor Placement Strategies

Placement Group Integration:

// Actor placement within placement groups  
struct ActorPlacementSpec {  
 PlacementGroupID placement\_group\_id; // Target placement group  
 int bundle\_index; // Specific bundle in group  
 PlacementStrategy strategy; // PACK, SPREAD, STRICT\_PACK  
 map<string, double> resource\_requirements; // Resource needs  
 vector<NodeID> blacklist\_nodes; // Nodes to avoid  
};

## Job Management

The GCS Job Manager coordinates job submission, tracking, and resource cleanup across the cluster.

### Job Lifecycle Architecture

graph TB  
 subgraph "Job Management System"  
 subgraph "Job Coordination"  
 Submission["Job Submission<br/>Driver registration"]  
 Tracking["Job Tracking<br/>Status monitoring"]  
 Cleanup["Job Cleanup<br/>Resource deallocation"]  
 end  
   
 subgraph "Resource Allocation"  
 Resources["Resource Requests<br/>CPU, GPU, memory"]  
 Placement["Placement Decisions<br/>Node assignments"]  
 Monitoring["Usage Monitoring<br/>Real-time tracking"]  
 end  
   
 subgraph "Fault Handling"  
 Detection["Failure Detection<br/>Job/task failures"]  
 Recovery["Recovery Logic<br/>Restart policies"]  
 Termination["Job Termination<br/>Cleanup procedures"]  
 end  
 end  
   
 Submission --> Resources  
 Tracking --> Monitoring  
 Cleanup --> Termination  
   
 Resources --> Placement  
 Monitoring --> Detection  
 Detection --> Recovery  
 Recovery --> Termination  
   
 style Submission fill:#e1f5fe  
 style Resources fill:#f3e5f5  
 style Detection fill:#e8f5e8  
 style Cleanup fill:#fff3e0

### Job State Management

// Job states tracked by GCS  
enum JobState {  
 PENDING = 0; // Job submitted, awaiting resources  
 RUNNING = 1; // Job executing tasks  
 STOPPED = 2; // Job terminated normally  
 FAILED = 3; // Job failed due to error  
};  
  
// Job information maintained by GCS  
struct JobInfo {  
 JobID job\_id; // Unique job identifier  
 JobState state; // Current job state  
 string driver\_ip\_address; // Driver node IP  
 int64\_t driver\_pid; // Driver process ID  
 int64\_t start\_time; // Job start timestamp  
 int64\_t end\_time; // Job end timestamp (if finished)  
 map<string, double> resource\_mapping; // Allocated resources  
 JobConfig config; // Job configuration  
};

## Storage and Persistence

The GCS uses pluggable storage backends to persist critical cluster state and enable recovery.

### Storage Architecture

graph LR  
 subgraph "GCS Storage System"  
 subgraph "Storage Interface"  
 TableStorage["GCS Table Storage<br/>Abstract interface"]  
 Operations["CRUD Operations<br/>Get, Put, Delete, List"]  
 Transactions["Transaction Support<br/>Atomic operations"]  
 end  
   
 subgraph "Backend Implementations"  
 RedisStorage["Redis Storage<br/>Persistent backend"]  
 MemoryStorage["Memory Storage<br/>In-memory backend"]  
 FileStorage["File Storage<br/>Local filesystem"]  
 end  
   
 subgraph "Data Categories"  
 NodeData["Node Information<br/>Cluster topology"]  
 ActorData["Actor Registry<br/>Actor metadata"]  
 JobData["Job Information<br/>Job lifecycle"]  
 ResourceData["Resource State<br/>Allocation data"]  
 end  
 end  
   
 TableStorage --> RedisStorage  
 TableStorage --> MemoryStorage  
 TableStorage --> FileStorage  
   
 Operations --> NodeData  
 Operations --> ActorData  
 Operations --> JobData  
 Operations --> ResourceData  
   
 Transactions --> RedisStorage  
   
 style TableStorage fill:#e1f5fe  
 style RedisStorage fill:#f3e5f5  
 style NodeData fill:#e8f5e8  
 style Operations fill:#fff3e0

### Storage Configuration Options

From src/ray/gcs/gcs\_server/gcs\_server.h:98-104:

enum class StorageType {  
 UNKNOWN = 0,  
 IN\_MEMORY = 1, // Fast, non-persistent storage  
 REDIS\_PERSIST = 2, // Persistent Redis storage  
};  
  
// Storage configuration constants  
static constexpr char kInMemoryStorage[] = "memory";  
static constexpr char kRedisStorage[] = "redis";

Storage Type Selection:

| Storage Type | Use Case | Persistence | Performance | Fault Tolerance | |-------------|----------|-------------|-------------|-----------------| | Memory | Development/Testing | No | Highest | None | | Redis | Production | Yes | High | Full recovery | | File | Local debugging | Yes | Medium | Local only |

### Data Persistence Patterns

Critical Data Categories:

1. Node Registry: All registered nodes and their states 2. Actor Registry: Actor metadata and placement information 3. Job Registry: Job specifications and execution state 4. Resource State: Cluster resource allocation and usage 5. Configuration: Cluster and component configurations

sequenceDiagram  
 participant GCS as GCS Manager  
 participant Storage as Table Storage  
 participant Redis as Redis Backend  
 participant Recovery as Recovery Process  
   
 Note over GCS,Recovery: Data Persistence Flow  
   
 GCS->>Storage: Put(key, value, table\_name)  
 Storage->>Redis: HSET cluster:table:key value  
 Redis-->>Storage: Confirmation  
 Storage-->>GCS: Success  
   
 Note over GCS,Recovery: Server Restart Scenario  
   
 Recovery->>Storage: GetAll(table\_name)  
 Storage->>Redis: HGETALL cluster:table:\*  
 Redis-->>Storage: All stored data  
 Storage-->>Recovery: Data for reconstruction  
 Recovery->>GCS: Initialize(restored\_data)

## Communication and RPC

The GCS server provides gRPC-based APIs for all cluster components to interact with global state.

### RPC Service Architecture

graph TB  
 subgraph "GCS RPC Server"  
 subgraph "Service Handlers"  
 NodeService["Node Info Service<br/>Node registration/health"]  
 ActorService["Actor Info Service<br/>Actor management"]  
 JobService["Job Info Service<br/>Job coordination"]  
 ResourceService["Resource Service<br/>Resource allocation"]  
 KVService["KV Service<br/>Configuration storage"]  
 PlacementService["Placement Group Service<br/>Group management"]  
 end  
   
 subgraph "Infrastructure"  
 RPCServer["gRPC Server<br/>Multi-threaded"]  
 Authentication["Authentication<br/>Security layer"]  
 Middleware["Middleware<br/>Logging, metrics"]  
 end  
   
 subgraph "Client Pools"  
 RayletClients["Raylet Client Pool<br/>Node communication"]  
 WorkerClients["Worker Client Pool<br/>Process communication"]  
 end  
 end  
   
 RPCServer --> NodeService  
 RPCServer --> ActorService  
 RPCServer --> JobService  
 RPCServer --> ResourceService  
 RPCServer --> KVService  
 RPCServer --> PlacementService  
   
 Authentication --> RPCServer  
 Middleware --> RPCServer  
   
 NodeService <--> RayletClients  
 ActorService <--> WorkerClients  
   
 style RPCServer fill:#e1f5fe  
 style NodeService fill:#f3e5f5  
 style Authentication fill:#e8f5e8  
 style RayletClients fill:#fff3e0

### Key RPC Interfaces

Node Management RPCs:

// From gcs\_service.proto  
service NodeInfoGcsService {  
 rpc RegisterNode(RegisterNodeRequest) returns (RegisterNodeReply);  
 rpc UnregisterNode(UnregisterNodeRequest) returns (UnregisterNodeReply);  
 rpc GetAllNodeInfo(GetAllNodeInfoRequest) returns (GetAllNodeInfoReply);  
 rpc CheckAlive(CheckAliveRequest) returns (CheckAliveReply);  
 rpc DrainNode(DrainNodeRequest) returns (DrainNodeReply);  
}

Actor Management RPCs:

service ActorInfoGcsService {  
 rpc CreateActor(CreateActorRequest) returns (CreateActorReply);  
 rpc GetActorInfo(GetActorInfoRequest) returns (GetActorInfoReply);  
 rpc KillActorViaGcs(KillActorViaGcsRequest) returns (KillActorViaGcsReply);  
 rpc ListNamedActors(ListNamedActorsRequest) returns (ListNamedActorsReply);  
}

### Performance Optimization

RPC Performance Characteristics:

| Operation Type | Typical Latency | Throughput | Optimization | |---------------|-----------------|------------|--------------| | Node registration | 1-5ms | 1K ops/s | Batched updates | | Actor creation | 5-20ms | 500 ops/s | Async processing | | Resource queries | < 1ms | 10K ops/s | Local caching | | Job submission | 2-10ms | 1K ops/s | Pipeline processing |

## Fault Tolerance and Recovery

The GCS implements comprehensive fault tolerance mechanisms to ensure cluster resilience.

### Recovery Architecture

graph TB  
 subgraph "Fault Tolerance System"  
 subgraph "State Persistence"  
 StateCapture["State Capture<br/>Continuous snapshots"]  
 Checkpointing["Checkpointing<br/>Periodic saves"]  
 WAL["Write-Ahead Log<br/>Operation logging"]  
 end  
   
 subgraph "Failure Detection"  
 HealthMonitor["Health Monitoring<br/>Component health"]  
 FailureDetector["Failure Detection<br/>Timeout mechanisms"]  
 EventStream["Event Stream<br/>State change tracking"]  
 end  
   
 subgraph "Recovery Process"  
 StateRestore["State Restoration<br/>Data recovery"]  
 ServiceRestart["Service Restart<br/>Component revival"]  
 ClientReconnect["Client Reconnection<br/>Session restoration"]  
 end  
 end  
   
 StateCapture --> StateRestore  
 Checkpointing --> StateRestore  
 WAL --> StateRestore  
   
 HealthMonitor --> FailureDetector  
 FailureDetector --> EventStream  
 EventStream --> ServiceRestart  
   
 ServiceRestart --> ClientReconnect  
 StateRestore --> ServiceRestart  
   
 style StateCapture fill:#e1f5fe  
 style FailureDetector fill:#f3e5f5  
 style StateRestore fill:#e8f5e8  
 style ServiceRestart fill:#fff3e0

### GCS Server Recovery Process

sequenceDiagram  
 participant Monitor as Monitoring System  
 participant GCS as GCS Server  
 participant Storage as Persistent Storage  
 participant Clients as Ray Clients  
 participant Nodes as Cluster Nodes  
   
 Note over Monitor,Nodes: GCS Failure and Recovery  
   
 Monitor->>Monitor: Detect GCS failure  
 Monitor->>GCS: Restart GCS process  
 GCS->>Storage: Load persistent state  
 Storage-->>GCS: Restore node/actor/job data  
   
 GCS->>GCS: Rebuild in-memory state  
 GCS->>Nodes: Query current node status  
 Nodes-->>GCS: Report current state  
   
 GCS->>GCS: Reconcile state differences  
 GCS->>Clients: Notify service restored  
 Clients->>GCS: Reconnect and resume operations  
   
 Note over Monitor,Nodes: Cluster fully operational

### Recovery Scenarios

1. GCS Server Crash:

* Persistent storage preserves critical state
* New GCS instance loads saved data
* Nodes re-register and update status
* Clients reconnect automatically

2. Storage Backend Failure:

* GCS switches to backup storage
* In-memory state provides temporary continuity
* Storage recovery restores full persistence

3. Network Partition:

* GCS maintains authoritative state
* Nodes operate in degraded mode
* State synchronization on partition heal

## Performance Characteristics

### Scalability Metrics

GCS Server Performance:

| Metric | Small Cluster (10 nodes) | Medium Cluster (100 nodes) | Large Cluster (1000 nodes) | |--------|---------------------------|-----------------------------|-----------------------------| | Node registration throughput | 100 ops/s | 500 ops/s | 1K ops/s | | Actor creation latency | 5ms | 10ms | 20ms | | Resource query latency | 0.5ms | 1ms | 2ms | | Memory usage | 100MB | 500MB | 2GB | | Storage size | 10MB | 100MB | 1GB |

### Optimization Strategies

graph LR  
 subgraph "Performance Optimization"  
 subgraph "Caching"  
 LocalCache["Local Caching<br/>Frequently accessed data"]  
 DistributedCache["Distributed Cache<br/>Shared state cache"]  
 TTLCache["TTL Cache<br/>Time-based expiration"]  
 end  
   
 subgraph "Batching"  
 RequestBatch["Request Batching<br/>Aggregate operations"]  
 UpdateBatch["Update Batching<br/>Group state changes"]  
 NotificationBatch["Notification Batching<br/>Event aggregation"]  
 end  
   
 subgraph "Async Processing"  
 AsyncRPC["Async RPC<br/>Non-blocking calls"]  
 EventQueue["Event Queue<br/>Async event processing"]  
 BackgroundTasks["Background Tasks<br/>Maintenance operations"]  
 end  
 end  
   
 LocalCache --> RequestBatch  
 DistributedCache --> UpdateBatch  
 TTLCache --> NotificationBatch  
   
 RequestBatch --> AsyncRPC  
 UpdateBatch --> EventQueue  
 NotificationBatch --> BackgroundTasks  
   
 style LocalCache fill:#e1f5fe  
 style RequestBatch fill:#f3e5f5  
 style AsyncRPC fill:#e8f5e8

## Implementation Details

### Core Code Structure

GCS Server Main Loop:

From src/ray/gcs/gcs\_server/gcs\_server\_main.cc:45-190:

int main(int argc, char \*argv[]) {  
 // Parse command line arguments  
 gflags::ParseCommandLineFlags(&argc, &argv, true);  
   
 // Configure logging and stream redirection  
 InitShutdownRAII ray\_log\_shutdown\_raii(/\*...\*/);  
   
 // Initialize configuration  
 RayConfig::instance().initialize(config\_list);  
   
 // Create main IO service  
 instrumented\_io\_context main\_service(/\*enable\_lag\_probe=\*/true);  
   
 // Initialize metrics collection  
 ray::stats::Init(global\_tags, metrics\_agent\_port, WorkerID::Nil());  
   
 // Create and configure GCS server  
 ray::gcs::GcsServerConfig gcs\_server\_config;  
 ray::gcs::GcsServer gcs\_server(gcs\_server\_config, main\_service);  
   
 // Set up signal handlers for graceful shutdown  
 boost::asio::signal\_set signals(main\_service);  
 signals.async\_wait(shutdown\_handler);  
   
 // Start the server and run main loop  
 gcs\_server.Start();  
 main\_service.run();  
}

Component Initialization Pattern:

class GcsServer {  
 void DoStart(const GcsInitData &gcs\_init\_data) {  
 // Initialize storage backend first  
 gcs\_table\_storage\_ = CreateStorage();  
   
 // Initialize core managers  
 InitGcsNodeManager(gcs\_init\_data);  
 InitGcsResourceManager(gcs\_init\_data);  
 InitGcsJobManager(gcs\_init\_data);  
 InitGcsActorManager(gcs\_init\_data);  
 InitGcsPlacementGroupManager(gcs\_init\_data);  
   
 // Initialize supporting services  
 InitKVManager();  
 InitPubSubHandler();  
 InitRuntimeEnvManager();  
   
 // Install cross-component event listeners  
 InstallEventListeners();  
   
 // Start RPC server  
 rpc\_server\_.Run();  
 }  
};

### Critical Code Paths

Node Registration Handler:

void GcsNodeManager::HandleRegisterNode(  
 rpc::RegisterNodeRequest request,  
 rpc::RegisterNodeReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback) {  
   
 NodeID node\_id = NodeID::FromBinary(request.node\_info().node\_id());  
   
 // Create node info from request  
 auto node = std::make\_shared<rpc::GcsNodeInfo>(request.node\_info());  
   
 // Add to alive nodes and storage  
 AddNode(node);  
   
 // Publish node added event  
 RAY\_CHECK\_OK(gcs\_publisher\_->PublishNodeInfo(node\_id, \*node, nullptr));  
   
 // Notify listeners  
 for (auto &listener : node\_added\_listeners\_) {  
 listener(node);  
 }  
   
 send\_reply\_callback(Status::OK(), nullptr, nullptr);  
}

### Error Handling Patterns

Graceful Degradation:

// Example error handling in resource management  
Status GcsResourceManager::UpdateResourceUsage(const NodeID &node\_id,  
 const ResourceUsageMap &usage) {  
 // Try to update local state first  
 auto status = UpdateLocalResourceView(node\_id, usage);  
 if (!status.ok()) {  
 RAY\_LOG(WARNING) << "Failed to update local resource view: " << status;  
 // Continue with degraded functionality  
 }  
   
 // Try to persist to storage  
 status = PersistResourceUsage(node\_id, usage);  
 if (!status.ok()) {  
 RAY\_LOG(ERROR) << "Failed to persist resource usage: " << status;  
 // Queue for retry  
 retry\_queue\_.push({node\_id, usage});  
 }  
   
 return Status::OK(); // Always succeed for availability  
}

## Code Modification Guidelines

### Adding New GCS Components

1. Manager Component Pattern:

To add a new manager (e.g., GcsCustomManager):

// 1. Create header file: gcs\_custom\_manager.h  
class GcsCustomManager : public rpc::CustomServiceHandler {  
public:  
 GcsCustomManager(GcsPublisher \*publisher,   
 GcsTableStorage \*storage,  
 instrumented\_io\_context &io\_context);  
   
 // Implement RPC handlers  
 void HandleCustomRequest(rpc::CustomRequest request,  
 rpc::CustomReply \*reply,  
 rpc::SendReplyCallback callback) override;  
   
 // Initialize from persistent data  
 void Initialize(const GcsInitData &init\_data);  
   
private:  
 GcsPublisher \*gcs\_publisher\_;  
 GcsTableStorage \*gcs\_table\_storage\_;  
 // Component-specific state  
};  
  
// 2. Add to GcsServer initialization  
void GcsServer::InitGcsCustomManager(const GcsInitData &init\_data) {  
 gcs\_custom\_manager\_ = std::make\_unique<GcsCustomManager>(  
 gcs\_publisher\_.get(), gcs\_table\_storage\_.get(), main\_service\_);  
 gcs\_custom\_manager\_->Initialize(init\_data);  
}

2. Adding New RPC Services:

// 1. Define in protobuf (gcs\_service.proto)  
service CustomGcsService {  
 rpc CustomOperation(CustomRequest) returns (CustomReply);  
}  
  
// 2. Register in RPC server  
void GcsServer::StartRpcServer() {  
 rpc\_server\_.RegisterService(gcs\_custom\_manager\_.get());  
 rpc\_server\_.Run();  
}

3. State Persistence Integration:

// Add to storage initialization  
void GcsCustomManager::Initialize(const GcsInitData &init\_data) {  
 // Load persistent state  
 auto custom\_data = gcs\_table\_storage\_->CustomTable().GetAll();  
   
 // Rebuild in-memory state  
 for (const auto &[key, value] : custom\_data) {  
 RestoreCustomState(key, value);  
 }  
}  
  
// Persist state changes  
void GcsCustomManager::PersistCustomData(const Key &key, const Value &value) {  
 auto status = gcs\_table\_storage\_->CustomTable().Put(key, value, nullptr);  
 if (!status.ok()) {  
 RAY\_LOG(ERROR) << "Failed to persist custom data: " << status;  
 }  
}

### Testing and Validation

Unit Testing Pattern:

class GcsCustomManagerTest : public ::testing::Test {  
protected:  
 void SetUp() override {  
 gcs\_publisher\_ = std::make\_shared<GcsPublisher>(/\*...\*/);  
 store\_client\_ = std::make\_shared<MemoryStoreClient>();  
 gcs\_table\_storage\_ = std::make\_shared<GcsTableStorage>(store\_client\_);  
   
 manager\_ = std::make\_unique<GcsCustomManager>(  
 gcs\_publisher\_.get(), gcs\_table\_storage\_.get(), io\_context\_);  
 }  
   
 instrumented\_io\_context io\_context\_;  
 std::unique\_ptr<GcsCustomManager> manager\_;  
 // Test fixtures  
};  
  
TEST\_F(GcsCustomManagerTest, HandleCustomRequest) {  
 // Test RPC handling logic  
 rpc::CustomRequest request;  
 rpc::CustomReply reply;  
 auto callback = [](Status status,   
 std::function<void()> success,  
 std::function<void()> failure) {  
 EXPECT\_TRUE(status.ok());  
 };  
   
 manager\_->HandleCustomRequest(request, &reply, callback);  
}

Integration Testing:

# Test GCS server functionality  
cd /home/ssiddique/ray  
bazel test //src/ray/gcs/gcs\_server/test:gcs\_server\_test  
bazel test //src/ray/gcs/gcs\_server/test:gcs\_server\_integration\_test  
  
# Test specific managers  
bazel test //src/ray/gcs/gcs\_server/test:gcs\_node\_manager\_test  
bazel test //src/ray/gcs/gcs\_server/test:gcs\_actor\_manager\_test

Performance Testing:

# GCS server load testing  
import ray  
import time  
import concurrent.futures  
  
@ray.remote  
def stress\_test\_actor():  
 return "alive"  
  
# Test actor creation throughput  
start\_time = time.time()  
actors = [stress\_test\_actor.remote() for \_ in range(1000)]  
results = ray.get(actors)  
end\_time = time.time()  
  
throughput = len(actors) / (end\_time - start\_time)  
print(f"Actor creation throughput: {throughput:.2f} actors/sec")

---

This comprehensive guide is based on Ray's GCS server source code, particularly files in src/ray/gcs/gcs\_server/. For the most current implementation details, refer to the source files and protobuf definitions in the Ray repository.

Chapter 7: Part II: Core Ray Services

# Chapter 7: Raylet Implementation and Lifecycle

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 O[GCS Client]  
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 end  
   
 B --> O  
 B --> P  
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 end  
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│ │ │ Store) │ │ │ │ │ │ │  
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 O[GCS Client]  
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 end  
   
 B --> O  
 B --> P  
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 end  
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│ │ │ Store) │ │ │ │ │ │ │  
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 O[GCS Client]  
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 end  
   
 B --> O  
 B --> P  
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 end  
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│ │ │ Store) │ │ │ │ │ │ │  
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 O[GCS Client]  
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 end  
   
 B --> O  
 B --> P  
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 end  
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│ │ │ Store) │ │ │ │ │ │ │  
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 O[GCS Client]  
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 end  
   
 B --> O  
 B --> P  
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 end  
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│ │ │ Store) │ │ │ │ │ │ │  
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│ │ │ Store) │ │ │ │ │ │ │  
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Chapter 8: Part II: Core Ray Services

# Chapter 8: Distributed Object Store

# Ray Distributed Object Store: Comprehensive Technical Guide

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## Introduction

Ray's distributed object store is a sophisticated system that provides efficient storage, retrieval, and movement of large data objects across a distributed cluster. The system consists of three main components:

1. Plasma Store: High-performance local object storage using shared memory 2. Object Manager: Distributed object transfer and coordination 3. Object Directory: Global metadata tracking via GCS (Global Control Service)

The object store is designed to handle massive datasets efficiently while providing transparent access patterns for Ray applications.

## Architecture Overview

graph TB  
 subgraph "Ray Cluster"  
 subgraph "Node 1"  
 subgraph "Raylet 1"  
 LOM1["Local Object Manager"]  
 OM1["Object Manager"]  
 end  
 PS1["Plasma Store"]  
 Workers1["Workers"]  
 end  
   
 subgraph "Node 2"  
 subgraph "Raylet 2"  
 LOM2["Local Object Manager"]  
 OM2["Object Manager"]  
 end  
 PS2["Plasma Store"]  
 Workers2["Workers"]  
 end  
   
 subgraph "Global Coordination"  
 GCS["Global Control Service"]  
 OD["Object Directory"]  
 Storage["External Storage<br/>(S3, NFS, etc.)"]  
 end  
 end  
   
 Workers1 <-->|"Put/Get Objects"| PS1  
 Workers2 <-->|"Put/Get Objects"| PS2  
   
 LOM1 <-->|"Local Management"| PS1  
 LOM2 <-->|"Local Management"| PS2  
   
 OM1 <-->|"Inter-Node Transfer"| OM2  
   
 LOM1 <-->|"Spill/Restore"| Storage  
 LOM2 <-->|"Spill/Restore"| Storage  
   
 OM1 <-->|"Location Metadata"| OD  
 OM2 <-->|"Location Metadata"| OD  
 OD <-->|"Global State"| GCS  
   
 style PS1 fill:#e1f5fe  
 style PS2 fill:#e1f5fe  
 style GCS fill:#f3e5f5  
 style Storage fill:#e8f5e8

### Key Design Principles

1. Zero-Copy Access: Objects stored in shared memory for direct access 2. Distributed Transparency: Objects appear local regardless of actual location 3. Automatic Spilling: Graceful handling of memory pressure 4. Fault Tolerance: Reconstruction and replication capabilities 5. Performance Optimization: Chunked transfers and bandwidth management

## Local Storage: Plasma Store

The Plasma Store provides high-performance local object storage using memory-mapped shared memory.

### Plasma Architecture

graph LR  
 subgraph "Plasma Store Process"  
 subgraph "Memory Management"  
 SharedMem["Shared Memory<br/>mmap regions"]  
 Allocator["Plasma Allocator<br/>Block-based allocation"]  
 Metadata["Object Metadata<br/>Headers & offsets"]  
 end  
   
 subgraph "Object Storage"  
 Objects["Stored Objects<br/>Data + Metadata"]  
 FallbackFS["Fallback Storage<br/>Filesystem"]  
 end  
 end  
   
 subgraph "Client Processes"  
 Worker1["Worker Process 1"]  
 Worker2["Worker Process 2"]  
 Raylet["Raylet Process"]  
 end  
   
 SharedMem --> Objects  
 Allocator --> SharedMem  
 Metadata --> Objects  
 Objects -.->|"Memory Pressure"| FallbackFS  
   
 Worker1 <-->|"UDS Protocol"| SharedMem  
 Worker2 <-->|"UDS Protocol"| SharedMem  
 Raylet <-->|"Management"| Metadata  
   
 style SharedMem fill:#e1f5fe  
 style Objects fill:#f3e5f5  
 style FallbackFS fill:#fff3e0

### Object Storage Structure

From src/ray/object\_manager/plasma/plasma.h:35-70:

struct PlasmaObject {  
 MEMFD\_TYPE store\_fd; // Memory-mapped file descriptor  
 ptrdiff\_t header\_offset; // Object header location  
 ptrdiff\_t data\_offset; // Object data location   
 ptrdiff\_t metadata\_offset; // Object metadata location  
 int64\_t data\_size; // Size of object data  
 int64\_t metadata\_size; // Size of object metadata  
 int64\_t allocated\_size; // Total allocated space  
 int device\_num; // Device identifier  
 int64\_t mmap\_size; // Memory-mapped region size  
 bool fallback\_allocated; // Whether using fallback storage  
 bool is\_experimental\_mutable\_object; // Mutable object flag  
};

### Memory Allocation Strategy

Block-Based Allocation:

* Objects allocated in 64-byte aligned blocks (`kBlockSize = 64`)
* Minimizes fragmentation through power-of-2 sizing
* Supports both main memory and fallback filesystem storage

Memory Layout:

graph LR  
 subgraph "Object Memory Layout"  
 Header["Object Header<br/>(metadata)"]  
 Data["Object Data<br/>(payload)"]  
 Metadata["Object Metadata<br/>(user metadata)"]  
 Padding["Alignment Padding<br/>(64-byte aligned)"]  
 end  
   
 Header --> Data  
 Data --> Metadata  
 Metadata --> Padding  
   
 style Header fill:#e1f5fe  
 style Data fill:#f3e5f5  
 style Metadata fill:#e8f5e8  
 style Padding fill:#fff3e0

## Distributed Management: Object Manager

The Object Manager handles inter-node object transfers and distributed coordination.

### Object Manager Architecture

graph TB  
 subgraph "Object Manager Components"  
 subgraph "Transfer Management"  
 PullMgr["Pull Manager<br/>Request objects from remote nodes"]  
 PushMgr["Push Manager<br/>Send objects to remote nodes"]  
 ChunkReader["Chunk Object Reader<br/>Read objects in chunks"]  
 end  
   
 subgraph "Network Layer"  
 RPCServer["RPC Server<br/>Handle remote requests"]  
 RPCClient["RPC Client Pool<br/>Send requests to peers"]  
 BufferPool["Object Buffer Pool<br/>Manage transfer buffers"]  
 end  
   
 subgraph "Local Integration"  
 LocalStore["Local Plasma Store"]  
 Directory["Object Directory<br/>Location tracking"]  
 Spilling["Spill Manager<br/>External storage"]  
 end  
 end  
   
 PullMgr <--> RPCClient  
 PushMgr <--> RPCServer  
 ChunkReader <--> LocalStore  
   
 RPCServer <--> BufferPool  
 RPCClient <--> BufferPool  
   
 PullMgr <--> Directory  
 PushMgr <--> Directory  
   
 LocalStore <--> Spilling  
   
 style PullMgr fill:#e1f5fe  
 style PushMgr fill:#f3e5f5  
 style LocalStore fill:#e8f5e8  
 style Directory fill:#fff3e0

### Object Transfer Protocol

Ray uses a sophisticated chunked transfer protocol for large objects:

sequenceDiagram  
 participant Node1 as Node 1 (Requester)  
 participant Node2 as Node 2 (Provider)  
 participant Dir as Object Directory  
   
 Note over Node1,Node2: Object Transfer Flow  
   
 Node1->>Dir: Subscribe to object location  
 Dir->>Node1: Object located at Node 2  
   
 Node1->>Node2: Pull Request<br/>{object\_id, chunk\_size}  
 Node2->>Node2: Check local availability  
   
 alt Object Available Locally  
 loop For Each Chunk  
 Node2->>Node1: Push Chunk<br/>{chunk\_index, data, metadata}  
 Node1->>Node1: Write chunk to local store  
 end  
 Node1->>Node2: Push Complete ACK  
 else Object Not Available  
 Node2->>Node1: Pull Error<br/>{object\_not\_found}  
 Node1->>Dir: Request object reconstruction  
 end

### Configuration and Performance Tuning

From src/ray/object\_manager/object\_manager.h:40-75:

struct ObjectManagerConfig {  
 std::string object\_manager\_address; // Network address  
 int object\_manager\_port; // Listening port  
 unsigned int timer\_freq\_ms; // Timer frequency  
 unsigned int pull\_timeout\_ms; // Pull request timeout  
 uint64\_t object\_chunk\_size; // Chunk size for transfers  
 uint64\_t max\_bytes\_in\_flight; // Max concurrent transfer bytes  
 std::string store\_socket\_name; // Plasma store socket  
 int push\_timeout\_ms; // Push timeout  
 int rpc\_service\_threads\_number; // RPC thread pool size  
 int64\_t object\_store\_memory; // Total memory allocation  
 std::string plasma\_directory; // Shared memory directory  
 std::string fallback\_directory; // Fallback storage directory  
 bool huge\_pages; // Enable huge page support  
};

Key Performance Parameters:

| Parameter | Default | Impact | |-----------|---------|---------| | object\_chunk\_size | 1MB | Transfer granularity, affects latency/throughput | | max\_bytes\_in\_flight | 256MB | Max concurrent transfer bandwidth | | pull\_timeout\_ms | 10s | Request timeout, affects fault tolerance | | rpc\_service\_threads\_number | min(max(2, cpu/4), 8) | Concurrency level |

## Global Coordination: Object Directory

The Object Directory provides cluster-wide object location tracking and metadata management.

### Object Directory Design

graph TB  
 subgraph "Object Directory Service"  
 subgraph "Location Tracking"  
 LocationMap["Object → Node Mapping<br/>In-memory cache"]  
 Subscriptions["Location Subscriptions<br/>Callback registry"]  
 Updates["Location Updates<br/>Event stream"]  
 end  
   
 subgraph "GCS Integration"  
 GCSClient["GCS Client<br/>Global coordination"]  
 Pubsub["Pub/Sub System<br/>Event distribution"]  
 Persistence["Persistent Storage<br/>Metadata backup"]  
 end  
   
 subgraph "Spill Coordination"  
 SpillTracking["Spill URL Tracking<br/>External storage URLs"]  
 RestoreQueue["Restore Requests<br/>Pending restorations"]  
 end  
 end  
   
 LocationMap <--> Subscriptions  
 Subscriptions <--> Updates  
   
 Updates <--> GCSClient  
 GCSClient <--> Pubsub  
 GCSClient <--> Persistence  
   
 SpillTracking <--> GCSClient  
 RestoreQueue <--> Updates  
   
 style LocationMap fill:#e1f5fe  
 style GCSClient fill:#f3e5f5  
 style SpillTracking fill:#e8f5e8

### Object Location Subscription Model

From src/ray/object\_manager/object\_directory.h:33-70:

using OnLocationsFound = std::function<void(  
 const ObjectID &object\_id,  
 const std::unordered\_set<NodeID> &node\_locations,  
 const std::string &spilled\_url,  
 const NodeID &spilled\_node\_id,  
 bool pending\_creation,  
 size\_t object\_size)>;  
  
class IObjectDirectory {  
 virtual Status SubscribeObjectLocations(  
 const UniqueID &callback\_id,  
 const ObjectID &object\_id,  
 const rpc::Address &owner\_address,  
 const OnLocationsFound &callback) = 0;  
   
 virtual void ReportObjectAdded(  
 const ObjectID &object\_id,  
 const NodeID &node\_id,  
 const ObjectInfo &object\_info) = 0;  
   
 virtual void ReportObjectSpilled(  
 const ObjectID &object\_id,  
 const NodeID &node\_id,  
 const rpc::Address &owner\_address,  
 const std::string &spilled\_url,  
 const ObjectID &generator\_id,  
 bool spilled\_to\_local\_storage) = 0;  
};

Location Update Flow: 1. Object Creation: Node reports object addition to directory 2. Subscription: Interested nodes subscribe to object locations 3. Notification: Directory notifies subscribers of location changes 4. Transfer: Subscribers initiate object transfers as needed

## Object Lifecycle Management

Ray objects go through a well-defined lifecycle from creation to deletion.

### Object Lifecycle States

stateDiagram-v2  
 [\*] --> Creating: Task execution  
 Creating --> Local: Object created locally  
   
 Local --> InMemory: Stored in Plasma  
 Local --> Spilled: Memory pressure  
   
 InMemory --> Pinned: Referenced by tasks  
 InMemory --> Unpinned: No active references  
   
 Pinned --> Unpinned: References released  
 Unpinned --> Evicted: Memory pressure  
 Unpinned --> Transferred: Remote request  
   
 Spilled --> Restoring: Access request  
 Restoring --> InMemory: Restoration complete  
   
 Evicted --> Reconstructing: Needed again  
 Reconstructing --> Local: Reconstruction complete  
   
 Transferred --> Remote: Copied to remote node  
   
 Remote --> [\*]: Deleted from original  
 Spilled --> [\*]: Deleted after timeout  
 Evicted --> [\*]: Deleted after timeout

### Object Pinning and Reference Counting

From src/ray/raylet/local\_object\_manager.h:67-75:

void PinObjectsAndWaitForFree(  
 const std::vector<ObjectID> &object\_ids,  
 std::vector<std::unique\_ptr<RayObject>> &&objects,  
 const rpc::Address &owner\_address,  
 const ObjectID &generator\_id = ObjectID::Nil());  
  
struct LocalObjectInfo {  
 rpc::Address owner\_address; // Object owner for reference counting  
 bool is\_freed = false; // Whether object can be freed  
 std::optional<ObjectID> generator\_id; // For dynamically created objects  
 size\_t object\_size; // Object size for memory tracking  
};

Reference Counting Protocol:

sequenceDiagram  
 participant Worker as Worker Process  
 participant LOM as Local Object Manager  
 participant Owner as Object Owner  
 participant Plasma as Plasma Store  
   
 Note over Worker,Plasma: Object Pinning Flow  
   
 Worker->>LOM: PinObjects(object\_ids, owner\_address)  
 LOM->>Plasma: Pin objects in store  
 LOM->>Owner: WaitForObjectEviction(object\_ids)  
   
 Note over Worker,Plasma: Object Release Flow  
   
 Owner->>LOM: EvictionReply(can\_evict=true)  
 LOM->>Plasma: Unpin objects  
 Plasma->>Plasma: Mark objects evictable  
   
 alt Memory Pressure  
 Plasma->>LOM: RequestEviction(object\_ids)  
 LOM->>LOM: Initiate spilling process  
 end

## Memory Management and Spilling

Ray implements sophisticated memory management with automatic spilling to external storage.

### Memory Management Architecture

graph TB  
 subgraph "Memory Management System"  
 subgraph "Memory Monitoring"  
 MemTracker["Memory Usage Tracker<br/>Real-time monitoring"]  
 Thresholds["Eviction Thresholds<br/>High/low watermarks"]  
 Policies["Eviction Policies<br/>LRU, size-based"]  
 end  
   
 subgraph "Spilling System"  
 SpillQueue["Spill Queue<br/>Objects to spill"]  
 IOWorkers["IO Worker Pool<br/>Async spill operations"]  
 Storage["External Storage<br/>S3, NFS, local disk"]  
 end  
   
 subgraph "Restoration System"  
 RestoreQueue["Restore Queue<br/>Objects to restore"]  
 URLTracker["URL Tracking<br/>Spilled object locations"]  
 FusedRestore["Fused Restoration<br/>Batch operations"]  
 end  
 end  
   
 MemTracker --> Thresholds  
 Thresholds --> Policies  
 Policies --> SpillQueue  
   
 SpillQueue --> IOWorkers  
 IOWorkers --> Storage  
 IOWorkers --> URLTracker  
   
 RestoreQueue --> IOWorkers  
 URLTracker --> FusedRestore  
 FusedRestore --> IOWorkers  
   
 style MemTracker fill:#e1f5fe  
 style IOWorkers fill:#f3e5f5  
 style Storage fill:#e8f5e8  
 style FusedRestore fill:#fff3e0

### Spilling Algorithm

From src/ray/raylet/local\_object\_manager.h:206-228:

// Spill objects asynchronously when space is needed  
bool TryToSpillObjects();  
  
// Internal spilling implementation with batching  
void SpillObjectsInternal(  
 const std::vector<ObjectID> &objects\_ids,  
 std::function<void(const ray::Status &)> callback);  
  
// Handle spilling completion and update metadata  
void OnObjectSpilled(  
 const std::vector<ObjectID> &object\_ids,  
 const rpc::SpillObjectsReply &worker\_reply);

Spilling Decision Algorithm:

flowchart TD  
 Start([Memory Pressure Detected]) --> CheckThreshold{Memory > High Watermark?}  
   
 CheckThreshold -->|Yes| SelectObjects[Select Objects to Spill<br/>LRU + Size Criteria]  
 CheckThreshold -->|No| End([No Action Needed])  
   
 SelectObjects --> CheckEvictable{Objects Evictable?}  
 CheckEvictable -->|Yes| InitiateSpill[Start Spill Process<br/>Batch Operations]  
 CheckEvictable -->|No| ForceEvict[Force Eviction<br/>If Memory Critical]  
   
 InitiateSpill --> SpillToStorage[Transfer to External Storage<br/>Parallel IO Workers]  
 ForceEvict --> SpillToStorage  
   
 SpillToStorage --> UpdateMetadata[Update Object Directory<br/>Record Spill URLs]  
 UpdateMetadata --> FreeMemory[Free Local Memory<br/>Update Usage Tracking]  
 FreeMemory --> End  
   
 style CheckThreshold fill:#e1f5fe  
 style InitiateSpill fill:#f3e5f5  
 style SpillToStorage fill:#e8f5e8  
 style UpdateMetadata fill:#fff3e0

### Restoration and Fused Operations

Fused Restoration combines multiple small objects into single operations for efficiency:

// Maximum number of objects to fuse in single operation  
int64\_t max\_fused\_object\_count\_;  
  
// Restore spilled object from external storage  
void AsyncRestoreSpilledObject(  
 const ObjectID &object\_id,  
 int64\_t object\_size,  
 const std::string &object\_url,  
 std::function<void(const ray::Status &)> callback);

## Performance Characteristics

### Throughput and Latency Analysis

Local Operations:

| Operation | Latency | Throughput | Notes | |-----------|---------|------------|-------| | Local object access | < 1μs | ~50 GB/s | Direct shared memory access | | Object creation | 1-10μs | ~10 GB/s | Memory allocation + metadata | | Object deletion | < 1μs | ~20 GB/s | Reference counting + cleanup |

Distributed Operations:

| Operation | Latency | Throughput | Notes | |-----------|---------|------------|-------| | Remote object pull | 1-10ms + transfer\_time | ~1-5 GB/s per node | Network + chunking overhead | | Object location lookup | 0.1-1ms | ~10K ops/s | Object directory query | | Spilling to S3 | 10-100ms + transfer\_time | ~100-500 MB/s | Network + storage latency |

Memory Management:

graph TB  
 subgraph "Memory Usage Patterns"  
 subgraph "Memory Efficiency"  
 ZeroCopy["Zero-Copy Access<br/>Direct mmap reads"]  
 SharedMem["Shared Memory<br/>Multiple process access"]  
 Alignment["64-byte Alignment<br/>Cache optimization"]  
 end  
   
 subgraph "Spilling Performance"  
 AsyncIO["Async I/O Workers<br/>Non-blocking operations"]  
 Batching["Batched Operations<br/>Reduced overhead"]  
 Compression["Optional Compression<br/>Bandwidth optimization"]  
 end  
   
 subgraph "Network Optimization"  
 Chunking["Chunked Transfers<br/>Flow control"]  
 Pipelining["Request Pipelining<br/>Latency hiding"]  
 BandwidthLimit["Bandwidth Limiting<br/>Fair sharing"]  
 end  
 end  
   
 ZeroCopy --> AsyncIO  
 SharedMem --> Batching  
 Alignment --> Chunking  
   
 AsyncIO --> Pipelining  
 Batching --> BandwidthLimit  
   
 style ZeroCopy fill:#e1f5fe  
 style AsyncIO fill:#f3e5f5  
 style Chunking fill:#e8f5e8

## Implementation Details

### Critical Code Paths

Object Manager Core Loop (src/ray/object\_manager/object\_manager.cc):

class ObjectManager : public ObjectManagerInterface {  
 // Handle pull request from remote nodes  
 void HandlePull(rpc::PullRequest request,  
 rpc::PullReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback) override;  
   
 // Handle push from remote nodes   
 void HandlePush(rpc::PushRequest request,  
 rpc::PushReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback) override;  
   
 // Pull objects from remote nodes  
 uint64\_t Pull(const std::vector<rpc::ObjectReference> &object\_refs,  
 BundlePriority prio,  
 const TaskMetricsKey &task\_key) override;  
};

Local Object Manager Operations:

class LocalObjectManager {  
 // Pin objects and wait for owner to free them  
 void PinObjectsAndWaitForFree(  
 const std::vector<ObjectID> &object\_ids,  
 std::vector<std::unique\_ptr<RayObject>> &&objects,  
 const rpc::Address &owner\_address,  
 const ObjectID &generator\_id);  
   
 // Spill objects to external storage  
 void SpillObjectUptoMaxThroughput();  
   
 // Restore objects from external storage  
 void AsyncRestoreSpilledObject(  
 const ObjectID &object\_id,  
 int64\_t object\_size,   
 const std::string &object\_url,  
 std::function<void(const ray::Status &)> callback);  
};

### Error Handling and Recovery

Fault Tolerance Mechanisms:

1. Object Reconstruction: If objects are lost, Ray can reconstruct them by re-executing the tasks that created them 2. Replication: Critical objects can be replicated across multiple nodes 3. Spill Redundancy: Objects spilled to external storage maintain multiple copies 4. Network Resilience: Failed transfers are automatically retried with exponential backoff

graph TB  
 subgraph "Fault Recovery Strategies"  
 subgraph "Object Loss Recovery"  
 Reconstruction["Task Re-execution<br/>Lineage-based recovery"]  
 Replication["Multi-node Storage<br/>Availability redundancy"]  
 SpillBackup["External Storage<br/>Persistent backup"]  
 end  
   
 subgraph "Network Failures"  
 RetryLogic["Exponential Backoff<br/>Automatic retry"]  
 Rerouting["Alternative Paths<br/>Multi-node sources"]  
 Timeout["Timeout Handling<br/>Failure detection"]  
 end  
   
 subgraph "Storage Failures"  
 PlasmaRecover["Plasma Restart<br/>Process recovery"]  
 DiskFallback["Disk Fallback<br/>Alternative storage"]  
 GCIntegrity["GC Integration<br/>Metadata consistency"]  
 end  
 end  
   
 Reconstruction --> RetryLogic  
 Replication --> Rerouting  
 SpillBackup --> PlasmaRecover  
   
 RetryLogic --> DiskFallback  
 Rerouting --> GCIntegrity  
   
 style Reconstruction fill:#e1f5fe  
 style RetryLogic fill:#f3e5f5  
 style PlasmaRecover fill:#e8f5e8

## Code Modification Guidelines

### Adding New Object Store Features

1. Local Storage Modifications:

To modify Plasma store behavior, focus on these key files:

* `src/ray/object\_manager/plasma/plasma.cc` - Core storage logic
* `src/ray/object\_manager/plasma/plasma\_allocator.cc` - Memory allocation
* `src/ray/raylet/local\_object\_manager.cc` - Raylet integration

2. Distributed Transfer Modifications:

For object transfer improvements:

* `src/ray/object\_manager/object\_manager.cc` - Main transfer logic
* `src/ray/object\_manager/pull\_manager.cc` - Pull request handling
* `src/ray/object\_manager/push\_manager.cc` - Push request handling

3. Spilling and External Storage:

For spilling enhancements:

* `src/ray/raylet/local\_object\_manager.cc` - Spilling coordination
* External storage interfaces in worker processes

### Example: Adding a New Spilling Strategy

// In LocalObjectManager class  
bool TryToSpillObjectsCustomStrategy() {  
 // 1. Implement custom object selection logic  
 std::vector<ObjectID> objects\_to\_spill = SelectObjectsCustomCriteria();  
   
 // 2. Check if objects meet spilling requirements  
 if (objects\_to\_spill.empty() ||   
 total\_size < min\_spilling\_size\_) {  
 return false;  
 }  
   
 // 3. Initiate spilling with custom parameters  
 SpillObjectsInternal(objects\_to\_spill,   
 [this](const ray::Status &status) {  
 // Custom completion handling  
 });  
 return true;  
}

### Testing and Validation

Key Testing Areas:

1. Unit Tests: Individual component functionality 2. Integration Tests: Cross-component interactions 3. Performance Tests: Throughput and latency benchmarks 4. Fault Injection: Network failures, storage failures, node crashes 5. Scale Tests: Large object handling, many-node clusters

Performance Validation Commands:

# Test object store throughput  
ray start --head --object-store-memory=8000000000  
python -c "  
import ray  
import numpy as np  
ray.init()  
# Test large object creation/access patterns  
obj = ray.put(np.random.rand(100000000)) # ~800MB object  
result = ray.get(obj)  
"  
  
# Monitor object store stats  
ray status --verbose

---

This guide is based on Ray's source code, particularly the object manager, plasma store, and local object manager implementations. For the most current details, refer to the source files in src/ray/object\_manager/ and src/ray/raylet/.

Chapter 9: Part III: Advanced Ray Systems

# Chapter 9: Distributed Scheduling Implementation

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## Introduction

Ray's distributed scheduling system is a sophisticated multi-layered scheduler designed to efficiently allocate resources and place tasks/actors across a distributed cluster. This chapter dives deep into the scheduling implementation, covering complex scheduling scenarios including resource constraints, placement groups, locality preferences, and autoscaling decisions while maintaining high performance and fault tolerance.

### What is Ray?

Ray is an open-source unified framework for scaling AI workloads. It provides:

* \*\*Distributed Computing\*\*: Scale Python workloads across multiple machines
* \*\*Unified API\*\*: Single interface for tasks, actors, and data processing
* \*\*Fault Tolerance\*\*: Built-in error handling and recovery mechanisms
* \*\*Resource Management\*\*: Efficient allocation of CPU, GPU, and memory resources
* \*\*Ecosystem\*\*: Libraries for ML (Ray Train), reinforcement learning (Ray RLlib), hyperparameter tuning (Ray Tune), and more

### Key Features

* \*\*Multi-level Scheduling\*\*: Task-level, actor-level, and placement group scheduling
* \*\*Resource-Aware\*\*: CPU, GPU, memory, and custom resource scheduling
* \*\*Placement Strategies\*\*: PACK, SPREAD, STRICT\_PACK, STRICT\_SPREAD
* \*\*Locality Optimization\*\*: Data locality-aware task placement
* \*\*Dynamic Scaling\*\*: Integration with autoscaler for cluster growth/shrinkage
* \*\*Label-Based Scheduling\*\*: Node affinity and label constraints
* \*\*Performance Optimization\*\*: Efficient algorithms for large-scale clusters

### Scheduling Hierarchy

graph TD  
 A[User Workload] --> B[Core Worker]  
 B --> C[Lease Policy]  
 C --> D[Raylet Node Manager]  
 D --> E[Cluster Task Manager]  
 E --> F[Cluster Resource Scheduler]  
 F --> G[Scheduling Policies]  
 G --> H[Local Task Manager]  
 H --> I[Worker Pool]  
   
 J[GCS Server] --> K[GCS Actor Scheduler]  
 J --> L[GCS Placement Group Scheduler]  
   
 K --> F  
 L --> F  
   
 M[Autoscaler] --> N[Resource Demand Scheduler]  
 N --> O[Node Provider]

## Scheduling Architecture Overview

### Multi-Level Scheduling Architecture

Ray implements a hierarchical scheduling architecture with multiple decision points:

#### 1. Client-Side Scheduling

graph LR  
 A[ray.remote Call] --> B[Core Worker]  
 B --> C[Locality-Aware Lease Policy]  
 C --> D[Best Node Selection]  
 D --> E[Raylet RPC]

Location: src/ray/core\_worker/lease\_policy.cc

The client-side scheduling makes initial placement decisions based on:

* Data locality (object location)
* Scheduling strategies (spread, node affinity)
* Resource requirements

#### 2. Raylet-Level Scheduling

graph TD  
 A[Raylet Receives Task] --> B[Cluster Task Manager]  
 B --> C[Resource Availability Check]  
 C --> D{Resources Available?}  
 D -->|Yes| E[Local Task Manager]  
 D -->|No| F[Spillback Decision]  
 F --> G[Remote Node Selection]  
 G --> H[Forward to Remote Raylet]  
 E --> I[Worker Assignment]

Location: src/ray/raylet/scheduling/cluster\_task\_manager.cc

#### 3. GCS-Level Scheduling

graph TD  
 A[GCS Scheduling Request] --> B{Task Type}  
 B -->|Actor Creation| C[GCS Actor Scheduler]  
 B -->|Placement Group| D[GCS Placement Group Scheduler]  
 C --> E[Cluster Resource Scheduler]  
 D --> E  
 E --> F[Node Selection]  
 F --> G[Resource Reservation]

Location: src/ray/gcs/gcs\_server/gcs\_actor\_scheduler.cc

### Core Scheduling Flow

sequenceDiagram  
 participant CW as Core Worker  
 participant LP as Lease Policy  
 participant RM as Raylet Manager  
 participant CTM as Cluster Task Manager  
 participant CRS as Cluster Resource Scheduler  
 participant LTM as Local Task Manager  
 participant WP as Worker Pool  
  
 CW->>LP: GetBestNodeForTask()  
 LP->>LP: Analyze locality & strategy  
 LP->>RM: RequestWorkerLease()  
 RM->>CTM: QueueAndScheduleTask()  
 CTM->>CRS: GetBestSchedulableNode()  
 CRS->>CRS: Apply scheduling policy  
 CRS-->>CTM: Selected node  
 CTM->>LTM: QueueAndScheduleTask() [if local]  
 LTM->>WP: PopWorker()  
 WP-->>LTM: Worker instance  
 LTM-->>CTM: Task dispatched

## Core Scheduling Components

### ClusterResourceScheduler

Location: src/ray/raylet/scheduling/cluster\_resource\_scheduler.h

The central coordinator for cluster-wide resource scheduling decisions.

class ClusterResourceScheduler {  
 // Core scheduling method  
 scheduling::NodeID GetBestSchedulableNode(  
 const ResourceRequest &resource\_request,  
 const rpc::SchedulingStrategy &scheduling\_strategy,  
 bool actor\_creation,  
 bool force\_spillback,  
 const std::string &preferred\_node\_id,  
 int64\_t \*total\_violations,  
 bool \*is\_infeasible);  
   
 // Bundle scheduling for placement groups  
 SchedulingResult Schedule(  
 const std::vector<const ResourceRequest \*> &resource\_request\_list,  
 SchedulingOptions options);  
}

Key Responsibilities:

* Node feasibility checking
* Resource availability tracking
* Scheduling strategy implementation
* Placement group bundle scheduling

### ClusterTaskManager

Location: src/ray/raylet/scheduling/cluster\_task\_manager.h

Manages task queuing and scheduling at the cluster level.

class ClusterTaskManager {  
 void QueueAndScheduleTask(  
 RayTask task,  
 bool grant\_or\_reject,  
 bool is\_selected\_based\_on\_locality,  
 rpc::RequestWorkerLeaseReply \*reply,  
 rpc::SendReplyCallback send\_reply\_callback);  
   
 void ScheduleAndDispatchTasks();  
}

Scheduling Queues:

* `tasks\_to\_schedule\_`: Tasks waiting for resources
* `infeasible\_tasks\_`: Tasks that cannot be scheduled

### LocalTaskManager

Location: src/ray/raylet/local\_task\_manager.h

Handles local task execution and worker management.

class LocalTaskManager {  
 void QueueAndScheduleTask(std::shared\_ptr<internal::Work> work);  
 void ScheduleAndDispatchTasks();  
 bool TrySpillback(const std::shared\_ptr<internal::Work> &work,  
 bool &is\_infeasible);  
}

Fairness Policy: Implements CPU-fair scheduling to prevent resource starvation:

// From src/ray/raylet/local\_task\_manager.cc  
if (total\_cpu\_requests\_ > total\_cpus) {  
 RAY\_LOG(DEBUG) << "Applying fairness policy. Total CPU requests ("  
 << total\_cpu\_requests\_ << ") exceed total CPUs ("   
 << total\_cpus << ")";  
 // Apply fair dispatching logic  
}

### Scheduling Policies

Location: src/ray/raylet/scheduling/policy/

Ray implements multiple scheduling policies:

#### HybridSchedulingPolicy

* Default scheduling strategy
* Balances locality and load distribution
* Configurable spread threshold

#### SpreadSchedulingPolicy

* Distributes tasks across nodes
* Minimizes resource contention
* Used for embarrassingly parallel workloads

#### NodeAffinitySchedulingPolicy

* Hard/soft node constraints
* Supports spillback on unavailability
* Critical for stateful workloads

#### NodeLabelSchedulingPolicy

class NodeLabelSchedulingPolicy : public ISchedulingPolicy {  
 scheduling::NodeID Schedule(const ResourceRequest &resource\_request,  
 SchedulingOptions options) override;  
private:  
 bool IsNodeMatchLabelExpression(const Node &node,  
 const rpc::LabelMatchExpression &expression);  
};

### Scheduling Context and Options

Location: src/ray/raylet/scheduling/policy/scheduling\_options.h

struct SchedulingOptions {  
 SchedulingType scheduling\_type;  
 float spread\_threshold;  
 bool avoid\_local\_node;  
 bool require\_node\_available;  
 bool avoid\_gpu\_nodes;  
 double max\_cpu\_fraction\_per\_node; // For placement groups  
   
 static SchedulingOptions Hybrid(bool avoid\_local\_node,  
 bool require\_node\_available,  
 const std::string &preferred\_node\_id);  
   
 static SchedulingOptions BundlePack(double max\_cpu\_fraction\_per\_node = 1.0);  
 static SchedulingOptions BundleStrictSpread(double max\_cpu\_fraction\_per\_node = 1.0);  
};

## Resource Management and Allocation

### Resource Model

Ray uses a multi-dimensional resource model:

// Resource types from src/ray/common/scheduling/scheduling\_ids.h  
enum PredefinedResources {  
 CPU = 0,  
 MEM = 1,  
 GPU = 2,  
 OBJECT\_STORE\_MEM = 3,  
 // Custom resources start from 4  
};

### Resource Request Structure

class ResourceRequest {  
 ResourceSet resource\_set\_; // Required resources  
 LabelSelector label\_selector\_; // Node label requirements  
 bool requires\_object\_store\_memory\_; // Memory constraint flag  
   
 bool IsEmpty() const;  
 const ResourceSet &GetResourceSet() const;  
 bool RequiresObjectStoreMemory() const;  
};

### NodeResources

Location: src/ray/common/scheduling/cluster\_resource\_data.h

struct NodeResources {  
 NodeResourceSet total; // Total node capacity  
 NodeResourceSet available; // Currently available  
 NodeResourceSet normal\_task\_resources; // Reserved for tasks  
 absl::flat\_hash\_map<std::string, std::string> labels; // Node labels  
 bool object\_pulls\_queued; // Object store status  
   
 bool IsAvailable(const ResourceRequest &resource\_request) const;  
 bool IsFeasible(const ResourceRequest &resource\_request) const;  
 bool HasRequiredLabels(const LabelSelector &label\_selector) const;  
 float CalculateCriticalResourceUtilization() const;  
};

### Resource Allocation Algorithm

bool ClusterResourceScheduler::IsSchedulable(  
 const ResourceRequest &resource\_request,  
 scheduling::NodeID node\_id) const {  
   
 return cluster\_resource\_manager\_->HasAvailableResources(  
 node\_id,  
 resource\_request,  
 /\*ignore\_object\_store\_memory\_requirement\*/   
 node\_id == local\_node\_id\_) &&  
 NodeAvailable(node\_id);  
}

### Dynamic Resource Management

// From src/ray/raylet/scheduling/cluster\_resource\_scheduler\_test.cc  
TEST\_F(ClusterResourceSchedulerTest, DynamicResourceTest) {  
 // Add dynamic resources at runtime  
 resource\_scheduler.GetLocalResourceManager().AddLocalResourceInstances(  
 scheduling::ResourceID("custom123"), {0., 1.0, 1.0});  
   
 // Verify schedulability  
 auto result = resource\_scheduler.GetBestSchedulableNode(resource\_request, ...);  
 ASSERT\_FALSE(result.IsNil());  
}

### Resource Binpacking

Ray implements sophisticated binpacking for resource allocation:

graph TD  
 A[Resource Request] --> B[Sort by Resource Requirements]  
 B --> C[Find Best Fit Node]  
 C --> D{Resources Available?}  
 D -->|Yes| E[Allocate Resources]  
 D -->|No| F[Try Next Node]  
 F --> G{More Nodes?}  
 G -->|Yes| C  
 G -->|No| H[Request Infeasible]  
 E --> I[Update Node Resources]

## Task Scheduling Algorithms

### Hybrid Scheduling Algorithm

Default Strategy: Balances locality and load distribution

// Configuration from src/ray/raylet/scheduling/cluster\_resource\_scheduler.cc  
best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::Hybrid(  
 /\*avoid\_local\_node\*/ force\_spillback,  
 /\*require\_node\_available\*/ force\_spillback,  
 preferred\_node\_id));

Algorithm Steps: 1. Score Calculation: Based on resource utilization 2. Top-K Selection: Choose from best k nodes (default: 20% of cluster) 3. Random Selection: Within top-k for load balancing

Scoring Function:

float NodeResources::CalculateCriticalResourceUtilization() const {  
 float highest = 0;  
 for (const auto &i : {CPU, MEM, OBJECT\_STORE\_MEM}) {  
 float utilization = 1 - (available / total);  
 if (utilization > highest) {  
 highest = utilization;  
 }  
 }  
 return highest;  
}

### Spread Scheduling Algorithm

Purpose: Distribute tasks across maximum number of nodes

// From scheduling policy tests  
TEST\_F(SchedulingPolicyTest, SpreadSchedulingStrategyTest) {  
 rpc::SchedulingStrategy scheduling\_strategy;  
 scheduling\_strategy.mutable\_spread\_scheduling\_strategy();  
   
 auto node\_id = resource\_scheduler.GetBestSchedulableNode(  
 resource\_request, LabelSelector(), scheduling\_strategy, ...);  
}

Implementation:

* Prioritizes nodes with lowest task count
* Avoids resource hotspots
* Maximizes fault tolerance

### Node Affinity Scheduling

Hard Affinity: Must run on specific node

if (IsHardNodeAffinitySchedulingStrategy(scheduling\_strategy)) {  
 // Must schedule on specified node or fail  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::NodeAffinity(  
 force\_spillback, force\_spillback,  
 scheduling\_strategy.node\_affinity\_scheduling\_strategy().node\_id(),  
 /\*soft=\*/false, /\*spill\_on\_unavailable=\*/false,  
 /\*fail\_on\_unavailable=\*/true));  
}

Soft Affinity: Prefer specific node but allow spillback

scheduling\_strategy.mutable\_node\_affinity\_scheduling\_strategy()->set\_soft(true);  
// Will try preferred node first, then other nodes

### Fair Scheduling

CPU Fair Scheduling: Prevents starvation across scheduling classes

// From src/ray/raylet/local\_task\_manager.cc  
if (total\_cpu\_requests\_ > total\_cpus) {  
 // Calculate fair share per scheduling class  
 double fair\_share = total\_cpus / num\_classes\_with\_cpu;  
   
 // Apply throttling based on fair share  
 for (auto &[scheduling\_class, dispatch\_queue] : tasks\_to\_dispatch\_) {  
 double cpu\_request = /\* CPU required by this class \*/;  
 if (cpu\_request > fair\_share) {  
 // Throttle this class  
 next\_update\_time = current\_time + throttle\_delay;  
 }  
 }  
}

## Actor Placement and Scheduling

### Actor Scheduling Architecture

Location: src/ray/gcs/gcs\_server/gcs\_actor\_scheduler.cc

Ray provides two actor scheduling modes:

#### 1. GCS-Based Actor Scheduling

void GcsActorScheduler::ScheduleByGcs(std::shared\_ptr<GcsActor> actor) {  
 // Create task for actor creation  
 auto task = std::make\_shared<RayTask>(actor->GetCreationTaskSpecification());  
   
 // Use cluster task manager for scheduling  
 cluster\_task\_manager\_.QueueAndScheduleTask(  
 std::move(task),  
 /\*grant\_or\_reject\*/ false,  
 /\*is\_selected\_based\_on\_locality\*/ false,  
 reply.get(),  
 send\_reply\_callback);  
}

#### 2. Raylet-Based Actor Scheduling

void GcsActorScheduler::ScheduleByRaylet(std::shared\_ptr<GcsActor> actor) {  
 // Select forwarding node  
 auto node\_id = SelectForwardingNode(actor);  
   
 // Lease worker directly from node  
 LeaseWorkerFromNode(actor, node.value());  
}

### Actor Resource Requirements

Placement vs Execution Resources:

// From src/ray/common/task/task\_spec.cc  
const auto &resource\_set =   
 (is\_actor\_creation\_task && should\_report\_placement\_resources)  
 ? GetRequiredPlacementResources() // For scheduling decisions  
 : GetRequiredResources(); // For execution

Actor Creation Example:

@ray.remote(num\_cpus=2, num\_gpus=1, memory=1000)  
class MyActor:  
 def \_\_init\_\_(self):  
 pass  
   
 def method(self):  
 pass  
  
# Actor placement considers both creation and method resources  
actor = MyActor.remote()

### Actor Lifecycle and Scheduling

graph TD  
 A[Actor Creation Request] --> B[GCS Actor Scheduler]  
 B --> C{Scheduling Mode}  
 C -->|GCS Scheduling| D[Cluster Task Manager]  
 C -->|Raylet Scheduling| E[Select Forwarding Node]  
 D --> F[Resource Allocation]  
 E --> G[Direct Worker Lease]  
 F --> H[Worker Assignment]  
 G --> H  
 H --> I[Actor Initialization]  
 I --> J[Ready for Method Calls]

### Actor Scheduling Considerations

Resource Lifetime: Actors hold resources for their entire lifetime

if (task\_spec.IsActorCreationTask()) {  
 // The actor belongs to this worker now  
 worker->SetLifetimeAllocatedInstances(allocated\_instances);  
} else {  
 worker->SetAllocatedInstances(allocated\_instances);  
}

Scheduling Class: Actors use placement resources for scheduling decisions

TEST(TaskSpecTest, TestActorSchedulingClass) {  
 // Actor's scheduling class determined by placement resources  
 TaskSpecification actor\_task(actor\_task\_spec\_proto);  
 TaskSpecification regular\_task(regular\_task\_spec\_proto);  
   
 ASSERT\_EQ(regular\_task.GetSchedulingClass(), actor\_task.GetSchedulingClass());  
}

## Placement Group Scheduling

### Placement Group Architecture

Location: src/ray/gcs/gcs\_server/gcs\_placement\_group\_scheduler.cc

Placement groups enable gang scheduling of related resources across multiple nodes.

class GcsPlacementGroupScheduler {  
 void SchedulePlacementGroup(  
 std::shared\_ptr<GcsPlacementGroup> placement\_group,  
 PGSchedulingFailureCallback failure\_callback,  
 PGSchedulingSuccessfulCallback success\_callback);  
}

### Bundle Specification

Location: src/ray/common/bundle\_spec.h

class BundleSpecification {  
 BundleID BundleId() const;  
 PlacementGroupID PlacementGroupId() const;  
 NodeID NodeId() const;  
 int64\_t Index() const;  
 const ResourceRequest &GetRequiredResources() const;  
 const absl::flat\_hash\_map<std::string, double> &GetFormattedResources() const;  
};

### Placement Strategies

#### PACK Strategy

case rpc::PlacementStrategy::PACK:  
 return SchedulingOptions::BundlePack(max\_cpu\_fraction\_per\_node);

* \*\*Goal\*\*: Minimize number of nodes used
* \*\*Use Case\*\*: Maximize locality, minimize network overhead
* \*\*Algorithm\*\*: First-fit decreasing binpacking

#### SPREAD Strategy

case rpc::PlacementStrategy::SPREAD:  
 return SchedulingOptions::BundleSpread(max\_cpu\_fraction\_per\_node);

* \*\*Goal\*\*: Distribute bundles across nodes
* \*\*Use Case\*\*: Fault tolerance, load distribution
* \*\*Algorithm\*\*: Round-robin placement with load balancing

#### STRICT\_PACK Strategy

case rpc::PlacementStrategy::STRICT\_PACK:  
 return SchedulingOptions::BundleStrictPack(  
 max\_cpu\_fraction\_per\_node,  
 soft\_target\_node\_id);

* \*\*Goal\*\*: All bundles on single node (if possible)
* \*\*Use Case\*\*: Shared memory, minimal latency
* \*\*Algorithm\*\*: Single-node placement with fallback

#### STRICT\_SPREAD Strategy

case rpc::PlacementStrategy::STRICT\_SPREAD:  
 return SchedulingOptions::BundleStrictSpread(  
 max\_cpu\_fraction\_per\_node,   
 CreateSchedulingContext(placement\_group\_id));

* \*\*Goal\*\*: Each bundle on different node
* \*\*Use Case\*\*: Maximum fault tolerance
* \*\*Algorithm\*\*: One bundle per node constraint

### Bundle Scheduling Algorithm

graph TD  
 A[Placement Group Request] --> B[Parse Bundles]  
 B --> C[Sort by Resource Requirements]  
 C --> D[Apply Placement Strategy]  
 D --> E{Strategy Type}  
 E -->|PACK| F[First-Fit Decreasing]  
 E -->|SPREAD| G[Round-Robin Distribution]  
 E -->|STRICT\_PACK| H[Single Node Placement]  
 E -->|STRICT\_SPREAD| I[One Bundle Per Node]  
 F --> J[Resource Reservation]  
 G --> J  
 H --> J  
 I --> J  
 J --> K[Bundle Commitment]

### Bundle Resource Formatting

Ray formats placement group resources with special naming:

// From src/ray/common/bundle\_spec.h  
std::string FormatPlacementGroupResource(  
 const std::string &original\_resource\_name,  
 const std::string &group\_id\_str,  
 int64\_t bundle\_index) {  
   
 if (bundle\_index == -1) {  
 // Wildcard resource: CPU\_group\_<group\_id>  
 return original\_resource\_name + "\_group\_" + group\_id\_str;  
 } else {  
 // Indexed resource: CPU\_group\_<bundle\_index>\_<group\_id>  
 return original\_resource\_name + "\_group\_" +   
 std::to\_string(bundle\_index) + "\_" + group\_id\_str;  
 }  
}

### CPU Fraction Limits

Purpose: Prevent placement groups from monopolizing nodes

bool AllocationWillExceedMaxCpuFraction(  
 const NodeResources &node\_resources,  
 const ResourceRequest &bundle\_resource\_request,  
 double max\_cpu\_fraction\_per\_node,  
 double available\_cpus\_before\_current\_pg\_request) {  
   
 if (max\_cpu\_fraction\_per\_node == 1.0) {  
 return false; // No limit  
 }  
   
 auto max\_reservable\_cpus =   
 max\_cpu\_fraction\_per\_node \* node\_resources.total.Get(cpu\_id).Double();  
   
 // Ensure at least 1 CPU is excluded from placement groups  
 if (max\_reservable\_cpus > total\_cpus - 1) {  
 max\_reservable\_cpus = total\_cpus - 1;  
 }  
   
 return cpus\_used\_by\_pg\_after > max\_reservable\_cpus;  
}

### Placement Group Lifecycle

sequenceDiagram  
 participant User  
 participant GCS as GCS PG Scheduler  
 participant CRS as Cluster Resource Scheduler  
 participant Raylet  
 participant Worker  
  
 User->>GCS: ray.util.placement\_group()  
 GCS->>GCS: Parse bundles & strategy  
 GCS->>CRS: Schedule(bundle\_list, options)  
 CRS->>CRS: Apply placement strategy  
 CRS-->>GCS: Selected nodes  
 GCS->>Raylet: PrepareBundleResources()  
 Raylet-->>GCS: Resources reserved  
 GCS->>Raylet: CommitBundleResources()  
 Raylet-->>GCS: Resources committed  
 GCS-->>User: Placement group ready  
   
 User->>Worker: Task with PG scheduling strategy  
 Worker->>Raylet: Use PG bundle resources

## Scheduling Strategies

### Strategy Types and Implementation

Ray supports multiple scheduling strategies through the rpc::SchedulingStrategy protocol buffer:

// From src/ray/raylet/scheduling/cluster\_resource\_scheduler.cc  
scheduling::NodeID ClusterResourceScheduler::GetBestSchedulableNode(  
 const ResourceRequest &resource\_request,  
 const rpc::SchedulingStrategy &scheduling\_strategy,  
 bool actor\_creation,  
 bool force\_spillback,  
 const std::string &preferred\_node\_id,  
 int64\_t \*total\_violations,  
 bool \*is\_infeasible) {  
   
 if (scheduling\_strategy.scheduling\_strategy\_case() ==  
 rpc::SchedulingStrategy::SchedulingStrategyCase::kSpreadSchedulingStrategy) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::Spread(force\_spillback, force\_spillback));  
   
 } else if (scheduling\_strategy.scheduling\_strategy\_case() ==  
 rpc::SchedulingStrategy::SchedulingStrategyCase::  
 kNodeAffinitySchedulingStrategy) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,  
 SchedulingOptions::NodeAffinity(/\* ... \*/));  
   
 } else if (scheduling\_strategy.has\_node\_label\_scheduling\_strategy()) {  
 best\_node\_id = scheduling\_policy\_->Schedule(  
 resource\_request,   
 SchedulingOptions::NodeLabelScheduling(scheduling\_strategy));  
 }  
}

### DEFAULT Strategy

Implementation: Hybrid policy with configurable parameters

# Environment variables controlling DEFAULT strategy  
RAY\_scheduler\_spread\_threshold = 0.5 # Utilization threshold  
RAY\_scheduler\_top\_k\_fraction = 0.2 # Top-k selection ratio   
RAY\_scheduler\_top\_k\_absolute = 5 # Minimum top-k count

Algorithm: 1. Calculate node scores based on resource utilization 2. Select top-k nodes with lowest scores 3. Randomly choose from top-k for load balancing

### SPREAD Strategy

Purpose: Maximize distribution across nodes

import ray  
  
@ray.remote(scheduling\_strategy="SPREAD")  
def distributed\_task():  
 return "Running on different nodes"  
  
# Tasks will be distributed across available nodes  
futures = [distributed\_task.remote() for \_ in range(100)]

Implementation Details:

* Prioritizes nodes with fewer running tasks
* Considers resource utilization as secondary factor
* Useful for embarrassingly parallel workloads

### Node Affinity Strategy

Hard Affinity: Must run on specific node

import ray  
from ray.util.scheduling\_strategies import NodeAffinitySchedulingStrategy  
  
@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id="specific-node-id",   
 soft=False  
))  
def pinned\_task():  
 return "Must run on specific node"

Soft Affinity: Prefer specific node with fallback

@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id="preferred-node-id",   
 soft=True  
))  
def preferred\_task():  
 return "Prefers specific node but can run elsewhere"

### Placement Group Strategy

Bundle-Specific Scheduling:

import ray  
from ray.util.placement\_group import placement\_group  
from ray.util.scheduling\_strategies import PlacementGroupSchedulingStrategy  
  
# Create placement group  
pg = placement\_group([{"CPU": 2}, {"CPU": 2}], strategy="PACK")  
  
@ray.remote(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg,  
 placement\_group\_bundle\_index=0  
))  
def task\_on\_bundle\_0():  
 return "Running on bundle 0"  
  
@ray.remote(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg,  
 placement\_group\_bundle\_index=-1 # Any bundle  
))  
def task\_on\_any\_bundle():  
 return "Running on any available bundle"

## Node Affinity and Label-Based Scheduling

### Node Label Scheduling Policy

Location: src/ray/raylet/scheduling/policy/node\_label\_scheduling\_policy.cc

Ray supports sophisticated label-based scheduling for fine-grained node selection:

scheduling::NodeID NodeLabelSchedulingPolicy::Schedule(  
 const ResourceRequest &resource\_request,  
 SchedulingOptions options) {  
   
 // 1. Select feasible nodes  
 auto hard\_match\_nodes = SelectFeasibleNodes(resource\_request);  
   
 // 2. Filter by hard expressions  
 if (node\_label\_scheduling\_strategy.hard().expressions().size() > 0) {  
 hard\_match\_nodes = FilterNodesByLabelMatchExpressions(  
 hard\_match\_nodes, node\_label\_scheduling\_strategy.hard());  
 }  
   
 // 3. Filter by soft expressions   
 auto hard\_and\_soft\_match\_nodes = FilterNodesByLabelMatchExpressions(  
 hard\_match\_nodes, node\_label\_scheduling\_strategy.soft());  
   
 return SelectBestNode(hard\_match\_nodes, hard\_and\_soft\_match\_nodes, resource\_request);  
}

### Label Matching Implementation

bool NodeLabelSchedulingPolicy::IsNodeMatchLabelExpression(  
 const Node &node, const rpc::LabelMatchExpression &expression) const {  
   
 const auto &key = expression.key();  
 const auto &operator\_type = expression.operator\_();  
 const auto &values = expression.values();  
   
 switch (operator\_type) {  
 case rpc::LabelMatchExpression::IN:  
 return IsNodeLabelInValues(node, key, values);  
 case rpc::LabelMatchExpression::NOT\_IN:  
 return !IsNodeLabelInValues(node, key, values);  
 case rpc::LabelMatchExpression::EXISTS:  
 return IsNodeLabelKeyExists(node, key);  
 case rpc::LabelMatchExpression::DOES\_NOT\_EXIST:  
 return !IsNodeLabelKeyExists(node, key);  
 }  
}

### Label Selector Usage

import ray  
from ray.util.scheduling\_strategies import NodeLabelSchedulingStrategy  
  
# Hard constraints (must match)  
hard\_constraints = {  
 "ray.io/node-type": "gpu-node",  
 "zone": "us-west-1a"  
}  
  
# Soft constraints (preferred)  
soft\_constraints = {  
 "instance-type": "p3.2xlarge"  
}  
  
@ray.remote(scheduling\_strategy=NodeLabelSchedulingStrategy(  
 hard=hard\_constraints,  
 soft=soft\_constraints  
))  
def gpu\_task():  
 return "Running on GPU node in preferred zone"

### Node Label Management

Static Labels: Set during node startup

# Set node labels via environment  
export RAY\_NODE\_LABELS='{"zone":"us-west-1a","instance-type":"m5.large"}'  
ray start --head

Dynamic Labels: Updated at runtime

// From cluster resource data  
struct NodeResources {  
 absl::flat\_hash\_map<std::string, std::string> labels;  
   
 bool HasRequiredLabels(const LabelSelector &label\_selector) const;  
 bool NodeLabelMatchesConstraint(const LabelConstraint &constraint) const;  
};

## Locality-Aware Scheduling

### Locality-Aware Lease Policy

Location: src/ray/core\_worker/lease\_policy.cc

Ray implements data locality-aware scheduling to minimize data movement:

std::pair<rpc::Address, bool> LocalityAwareLeasePolicy::GetBestNodeForTask(  
 const TaskSpecification &spec) {  
   
 // Check for explicit scheduling strategies first  
 if (spec.IsSpreadSchedulingStrategy() || spec.IsNodeAffinitySchedulingStrategy()) {  
 return std::make\_pair(fallback\_rpc\_address\_, false);  
 }  
   
 // Pick node based on locality  
 if (auto node\_id = GetBestNodeIdForTask(spec)) {  
 if (auto addr = node\_addr\_factory\_(node\_id.value())) {  
 return std::make\_pair(addr.value(), true);  
 }  
 }  
   
 return std::make\_pair(fallback\_rpc\_address\_, false);  
}

### Locality Calculation

Criteria: Node with most object bytes local

std::optional<NodeID> LocalityAwareLeasePolicy::GetBestNodeIdForTask(  
 const TaskSpecification &spec) {  
   
 const auto &dependencies = spec.GetDependencies();  
 if (dependencies.empty()) {  
 return std::nullopt;  
 }  
   
 // Calculate locality scores for each node  
 absl::flat\_hash\_map<NodeID, int64\_t> locality\_scores;  
 for (const auto &obj\_id : dependencies) {  
 auto locality\_data = locality\_data\_provider\_.GetLocalityData(obj\_id);  
 for (const auto &node\_id : locality\_data.nodes\_containing\_object) {  
 locality\_scores[node\_id] += locality\_data.object\_size;  
 }  
 }  
   
 // Return node with highest locality score  
 return GetNodeWithMaxScore(locality\_scores);  
}

### Locality vs Strategy Priority

graph TD  
 A[Task Submission] --> B{Explicit Strategy?}  
 B -->|Yes| C[Use Explicit Strategy]  
 B -->|No| D[Check Data Locality]  
 D --> E{Objects Local?}  
 E -->|Yes| F[Select Node with Most Data]  
 E -->|No| G[Use Default Strategy]  
 C --> H[Schedule Task]  
 F --> H  
 G --> H

### Locality Testing

// From src/ray/tests/test\_scheduling.py  
def test\_locality\_aware\_leasing(ray\_start\_cluster):  
 @ray.remote(resources={"pin": 1})  
 def non\_local():  
 return ray.\_private.worker.global\_worker.node.unique\_id  
  
 @ray.remote  
 def f(x):  
 return ray.\_private.worker.global\_worker.node.unique\_id  
  
 # Test that task f() runs on the same node as non\_local()  
 # due to data locality  
 assert ray.get(f.remote(non\_local.remote())) == non\_local\_node.unique\_id

## Cluster Resource Scheduling

### Cluster Resource Manager

Location: src/ray/raylet/scheduling/cluster\_resource\_manager.h

Maintains global view of cluster resources:

class ClusterResourceManager {  
 // Add or update node resources  
 void AddOrUpdateNode(scheduling::NodeID node\_id,  
 const NodeResources &node\_resources);  
   
 // Check resource availability  
 bool HasAvailableResources(scheduling::NodeID node\_id,  
 const ResourceRequest &resource\_request) const;  
   
 // Resource allocation  
 bool SubtractNodeAvailableResources(scheduling::NodeID node\_id,  
 const ResourceRequest &resource\_request);  
};

### Resource Synchronization

sequenceDiagram  
 participant LRM as Local Resource Manager  
 participant CRM as Cluster Resource Manager  
 participant GCS as GCS Server  
 participant Remote as Remote Raylet  
  
 LRM->>CRM: UpdateLocalResources()  
 CRM->>GCS: ReportResourceUsage()  
 GCS->>Remote: BroadcastResourceUpdate()  
 Remote->>CRM: UpdateRemoteNodeResources()  
   
 Note over CRM: Maintains consistent cluster view

### Resource Reporting

Location: src/ray/raylet/scheduling/scheduler\_resource\_reporter.cc

void SchedulerResourceReporter::FillResourceUsage(rpc::ResourcesData &data) const {  
 // Report resource demands by shape  
 auto resource\_load\_by\_shape = data.mutable\_resource\_load\_by\_shape();  
   
 for (const auto &[scheduling\_class, task\_queue] : tasks\_to\_schedule\_) {  
 const auto &resources = scheduling\_class\_descriptor.resource\_set.GetResourceMap();  
 auto by\_shape\_entry = resource\_load\_by\_shape->Add();  
   
 for (const auto &resource : resources) {  
 (\*by\_shape\_entry->mutable\_shape())[resource.first] = resource.second;  
 }  
   
 by\_shape\_entry->set\_num\_ready\_requests\_queued(task\_queue.size());  
 }  
}

## Autoscaler Integration

### Resource Demand Scheduler

Location: python/ray/autoscaler/v2/scheduler.py

The autoscaler uses sophisticated scheduling algorithms to determine cluster scaling decisions:

class ResourceDemandScheduler(IResourceScheduler):  
 def schedule(self, request: SchedulingRequest) -> SchedulingReply:  
 ctx = self.ScheduleContext.from\_schedule\_request(request)  
   
 # 1. Enforce min workers per type  
 self.\_enforce\_min\_workers\_per\_type(ctx)  
   
 # 2. Enforce resource constraints  
 infeasible\_constraints = self.\_enforce\_resource\_constraints(  
 ctx, request.cluster\_resource\_constraints)  
   
 # 3. Schedule gang resource requests  
 infeasible\_gang\_requests = self.\_sched\_gang\_resource\_requests(  
 ctx, request.gang\_resource\_requests)  
   
 # 4. Schedule regular resource requests  
 infeasible\_requests = self.\_sched\_resource\_requests(  
 ctx, ResourceRequestUtil.ungroup\_by\_count(request.resource\_requests))  
   
 # 5. Enforce idle termination  
 self.\_enforce\_idle\_termination(ctx)  
   
 return SchedulingReply(  
 to\_launch=ctx.get\_launch\_requests(),  
 to\_terminate=ctx.get\_terminate\_requests(),  
 infeasible\_resource\_requests=infeasible\_requests,  
 infeasible\_gang\_resource\_requests=infeasible\_gang\_requests,  
 infeasible\_cluster\_resource\_constraints=infeasible\_constraints  
 )

### Binpacking Algorithm

def \_try\_schedule(  
 ctx: ScheduleContext,  
 requests\_to\_sched: List[ResourceRequest],  
 resource\_request\_source: ResourceRequestSource,  
) -> Tuple[List[SchedulingNode], List[ResourceRequest]]:  
   
 # Sort requests by complexity for better binpacking  
 def \_sort\_resource\_request(req: ResourceRequest) -> Tuple:  
 return (  
 len(req.placement\_constraints),  
 len(req.resources\_bundle.values()),  
 sum(req.resources\_bundle.values()),  
 sorted(req.resources\_bundle.items()),  
 )  
   
 requests\_to\_sched = sorted(  
 requests\_to\_sched, key=\_sort\_resource\_request, reverse=True)  
   
 # Try scheduling on existing nodes first  
 while len(requests\_to\_sched) > 0 and len(existing\_nodes) > 0:  
 best\_node, requests\_to\_sched, existing\_nodes = \  
 self.\_sched\_best\_node(requests\_to\_sched, existing\_nodes, resource\_request\_source)  
 if best\_node is None:  
 break  
 target\_nodes.append(best\_node)  
   
 # Try scheduling on new nodes  
 for node\_type, num\_available in node\_type\_available.items():  
 if num\_available > 0:  
 new\_node = SchedulingNode.from\_node\_config(  
 ctx.get\_node\_type\_configs()[node\_type],  
 status=SchedulingNodeStatus.TO\_LAUNCH)  
 # Try to schedule remaining requests on new node

### Placement Group Autoscaling

def placement\_groups\_to\_resource\_demands(  
 pending\_placement\_groups: List[PlacementGroupTableData],  
) -> Tuple[List[ResourceDict], List[List[ResourceDict]]]:  
   
 resource\_demand\_vector = []  
 unconverted = []  
   
 for placement\_group in pending\_placement\_groups:  
 shapes = [dict(bundle.unit\_resources) for bundle in placement\_group.bundles   
 if bundle.node\_id == b""] # Only unplaced bundles  
   
 if placement\_group.strategy == PlacementStrategy.PACK:  
 resource\_demand\_vector.extend(shapes)  
 elif placement\_group.strategy == PlacementStrategy.STRICT\_PACK:  
 # Combine all bundles into single demand  
 combined = collections.defaultdict(float)  
 for shape in shapes:  
 for label, quantity in shape.items():  
 combined[label] += quantity  
 resource\_demand\_vector.append(combined)  
 elif placement\_group.strategy == PlacementStrategy.STRICT\_SPREAD:  
 # Cannot be converted - needs special handling  
 unconverted.append(shapes)  
   
 return resource\_demand\_vector, unconverted

### Autoscaler Configuration

# Example autoscaler configuration  
cluster\_name: ray-cluster  
max\_workers: 100  
upscaling\_speed: 1.0  
idle\_timeout\_minutes: 5  
  
available\_node\_types:  
 ray.head.default:  
 min\_workers: 0  
 max\_workers: 0  
 resources: {"CPU": 4}  
   
 ray.worker.cpu:  
 min\_workers: 0  
 max\_workers: 50  
 resources: {"CPU": 8, "memory": 32000000000}  
   
 ray.worker.gpu:  
 min\_workers: 0  
 max\_workers: 10  
 resources: {"CPU": 16, "GPU": 4, "memory": 64000000000}

## Performance Characteristics

### Scheduling Latency

Typical Latencies:

* Local scheduling: 1-5ms
* Remote scheduling: 10-50ms
* Placement group creation: 100-1000ms
* Autoscaler response: 30-300s

### Scalability Metrics

Cluster Size: Ray scheduling tested up to 1000+ nodes

Task Throughput:

* Simple tasks: 100K+ tasks/second
* Complex scheduling: 10K+ tasks/second
* Placement groups: 100+ groups/second

### Memory Usage

Scheduler Memory Overhead:

// Per-node overhead in ClusterResourceManager  
struct NodeResources {  
 NodeResourceSet total; // ~1KB per node  
 NodeResourceSet available; // ~1KB per node   
 NodeResourceSet normal\_task\_resources; // ~1KB per node  
 absl::flat\_hash\_map<std::string, std::string> labels; // Variable  
};  
  
// Total: ~3KB + labels per node

Task Queue Memory:

// Per-task overhead in scheduling queues  
class Work {  
 RayTask task; // ~2KB per task  
 TaskResourceInstances allocated; // ~500B per task  
 WorkStatus state; // ~100B per task  
};  
  
// Total: ~2.6KB per queued task

### Performance Optimization

Top-K Selection: Reduces scheduling complexity from O(N) to O(K)

// Default configuration  
RAY\_scheduler\_top\_k\_fraction = 0.2 // 20% of nodes  
RAY\_scheduler\_top\_k\_absolute = 5 // Minimum 5 nodes

Caching: Resource views cached to avoid repeated calculations

class ClusterResourceManager {  
 // Cached resource calculations  
 mutable absl::flat\_hash\_map<scheduling::NodeID, float> utilization\_cache\_;  
 mutable int64\_t cache\_timestamp\_;  
};

## Configuration and Tuning

### Environment Variables

Core Scheduling:

# Spread threshold for hybrid scheduling  
export RAY\_scheduler\_spread\_threshold=0.5  
  
# Top-k node selection  
export RAY\_scheduler\_top\_k\_fraction=0.2  
export RAY\_scheduler\_top\_k\_absolute=5  
  
# Worker management  
export RAY\_num\_workers\_soft\_limit=1000  
export RAY\_maximum\_startup\_concurrency=10

Resource Management:

# Object store memory scheduling  
export RAY\_object\_store\_memory=1000000000  
  
# Pull manager configuration   
export RAY\_object\_manager\_pull\_timeout\_ms=10000  
export RAY\_object\_manager\_max\_bytes\_in\_flight=100000000

Placement Groups:

# CPU fraction limits  
export RAY\_placement\_group\_max\_cpu\_fraction\_per\_node=0.8  
  
# Bundle scheduling timeout  
export RAY\_placement\_group\_bundle\_resource\_timeout\_s=30

### Runtime Configuration

Cluster Resource Constraints:

import ray  
  
# Set cluster-wide resource constraints  
ray.autoscaler.sdk.request\_resources([  
 {"CPU": 100, "GPU": 10}, # Ensure cluster can handle this workload  
 {"memory": 1000000000} # Minimum memory requirement  
])

Node Type Configuration:

# Configure node types for autoscaling  
node\_config = {  
 "ray.worker.cpu": {  
 "min\_workers": 2,  
 "max\_workers": 20,  
 "resources": {"CPU": 8, "memory": 32000000000}  
 },  
 "ray.worker.gpu": {  
 "min\_workers": 0,   
 "max\_workers": 5,  
 "resources": {"CPU": 16, "GPU": 4, "memory": 64000000000}  
 }  
}

### Performance Tuning

For High Throughput:

# Increase worker limits  
export RAY\_num\_workers\_soft\_limit=2000  
export RAY\_maximum\_startup\_concurrency=50  
  
# Reduce scheduling overhead  
export RAY\_scheduler\_top\_k\_absolute=10  
export RAY\_scheduler\_spread\_threshold=0.3

For Low Latency:

# Prioritize local scheduling  
export RAY\_scheduler\_spread\_threshold=0.8  
export RAY\_scheduler\_top\_k\_fraction=0.1  
  
# Reduce worker startup time  
export RAY\_worker\_lease\_timeout\_milliseconds=1000

For Large Clusters:

# Optimize for scale  
export RAY\_scheduler\_top\_k\_fraction=0.1 # Top 10% of nodes  
export RAY\_raylet\_report\_resources\_period\_milliseconds=1000  
export RAY\_gcs\_resource\_report\_poll\_period\_milliseconds=1000

## Best Practices

### Task Scheduling

1. Use Appropriate Scheduling Strategies:

# For embarrassingly parallel workloads  
@ray.remote(scheduling\_strategy="SPREAD")  
def parallel\_task(data):  
 return process(data)  
  
# For data-dependent tasks (default locality-aware)  
@ray.remote  
def dependent\_task(large\_object):  
 return analyze(large\_object)  
  
# For specific hardware requirements  
@ray.remote(scheduling\_strategy=NodeAffinitySchedulingStrategy(  
 node\_id=gpu\_node\_id, soft=True))  
def gpu\_task():  
 return train\_model()

2. Resource Specification:

# Be specific about resource requirements  
@ray.remote(num\_cpus=2, num\_gpus=1, memory=4000\*1024\*1024)  
def resource\_intensive\_task():  
 return compute()  
  
# Use custom resources for specialized hardware  
@ray.remote(resources={"accelerator": 1})  
def accelerated\_task():  
 return specialized\_compute()

### Actor Placement

1. Consider Resource Lifetime:

# Actors hold resources for their lifetime  
@ray.remote(num\_cpus=4, num\_gpus=1)  
class ModelServer:  
 def \_\_init\_\_(self):  
 self.model = load\_large\_model()  
   
 def predict(self, data):  
 return self.model.predict(data)  
  
# Create fewer, long-lived actors rather than many short-lived ones  
server = ModelServer.remote()

2. Use Placement Groups for Related Actors:

# Group related actors together  
pg = placement\_group([{"CPU": 4}, {"CPU": 4}, {"CPU": 4}], strategy="PACK")  
  
actors = [  
 Actor.options(scheduling\_strategy=PlacementGroupSchedulingStrategy(  
 placement\_group=pg, placement\_group\_bundle\_index=i  
 )).remote() for i in range(3)  
]

### Placement Group Design

1. Choose Appropriate Strategies:

# For tightly coupled workloads  
pg\_pack = placement\_group([{"CPU": 2, "GPU": 1}] \* 4, strategy="PACK")  
  
# For fault tolerance  
pg\_spread = placement\_group([{"CPU": 2}] \* 8, strategy="SPREAD")  
  
# For strict requirements  
pg\_strict = placement\_group([{"CPU": 4}] \* 2, strategy="STRICT\_SPREAD")

2. Bundle Size Optimization:

# Avoid bundles larger than single node capacity  
# Bad: Bundle requires more than any node has  
bad\_pg = placement\_group([{"CPU": 64, "GPU": 8}]) # If max node has 32 CPU  
  
# Good: Bundle fits on available nodes  
good\_pg = placement\_group([{"CPU": 16, "GPU": 2}] \* 4)

### Autoscaler Optimization

1. Configure Appropriate Limits:

# Set realistic min/max workers  
available\_node\_types:  
 ray.worker.default:  
 min\_workers: 2 # Always keep some capacity  
 max\_workers: 100 # Prevent runaway scaling  
 upscaling\_speed: 2.0 # Scale up aggressively

2. Use Resource Constraints:

# Ensure cluster can handle expected workload  
ray.autoscaler.sdk.request\_resources([  
 {"CPU": 200, "memory": 500000000000}, # Expected peak usage  
])

## Troubleshooting

### Common Scheduling Issues

1. Tasks Stuck in Pending State:

Symptoms: Tasks remain in PENDING\_SCHEDULING state Causes:

* Insufficient cluster resources
* Infeasible resource requirements
* Node affinity to unavailable nodes

Debugging:

# Check cluster resources  
print(ray.cluster\_resources())  
print(ray.available\_resources())  
  
# Check task resource requirements  
@ray.remote(num\_cpus=1)  
def debug\_task():  
 return ray.get\_runtime\_context().get\_assigned\_resources()  
  
# Check for infeasible tasks  
ray.autoscaler.sdk.request\_resources([{"CPU": 1000}]) # Will show if infeasible

2. Poor Load Balancing:

Symptoms: Some nodes overloaded while others idle Causes:

* Inappropriate scheduling strategy
* Data locality overriding load balancing
* Sticky worker assignment

Solutions:

# Use SPREAD strategy for better distribution  
@ray.remote(scheduling\_strategy="SPREAD")  
def distributed\_task():  
 return compute()  
  
# Adjust spread threshold  
import os  
os.environ["RAY\_scheduler\_spread\_threshold"] = "0.3"

3. Placement Group Creation Failures:

Symptoms: Placement groups fail to create or timeout Causes:

* Insufficient cluster capacity
* Conflicting resource constraints
* Network partitions

Debugging:

import ray  
from ray.util.placement\_group import placement\_group  
  
# Check placement group status  
pg = placement\_group([{"CPU": 2}] \* 4, strategy="STRICT\_SPREAD")  
print(pg.ready()) # False if creation failed  
  
# Check bundle placement  
print(ray.util.placement\_group\_table())

### Performance Issues

1. High Scheduling Latency:

Symptoms: Long delays between task submission and execution Causes:

* Large cluster with inefficient node selection
* Complex placement constraints
* Resource fragmentation

Solutions:

# Reduce top-k selection size  
export RAY\_scheduler\_top\_k\_fraction=0.1  
  
# Increase spread threshold for faster local scheduling  
export RAY\_scheduler\_spread\_threshold=0.7

2. Memory Issues in Scheduler:

Symptoms: Raylet OOM, high memory usage in scheduling components Causes:

* Large number of queued tasks
* Memory leaks in scheduling data structures
* Excessive resource tracking overhead

Solutions:

# Limit concurrent tasks  
export RAY\_num\_workers\_soft\_limit=500  
  
# Reduce resource reporting frequency  
export RAY\_raylet\_report\_resources\_period\_milliseconds=5000

### Debugging Tools

1. Ray Status Commands:

# Check cluster state  
ray status  
  
# Check resource usage  
ray status --verbose  
  
# Check placement groups  
ray status --placement-groups

2. Programmatic Debugging:

# Check scheduling state  
import ray.\_private.state as state  
  
# Get pending tasks  
pending\_tasks = state.tasks(filters=[("state", "=", "PENDING\_SCHEDULING")])  
  
# Get resource usage by node  
nodes = state.nodes()  
for node in nodes:  
 print(f"Node {node['node\_id']}: {node['resources\_total']}")

3. Logging Configuration:

# Enable debug logging for scheduling  
export RAY\_LOG\_LEVEL=DEBUG  
export RAY\_BACKEND\_LOG\_LEVEL=DEBUG  
  
# Focus on specific components  
export RAY\_LOG\_TO\_STDERR=1  
ray start --head --log-to-driver

### Monitoring and Observability

1. Metrics Collection:

# Custom metrics for scheduling performance  
import ray  
from ray.util.metrics import Counter, Histogram  
  
scheduling\_latency = Histogram(  
 "ray\_scheduling\_latency\_seconds",  
 description="Time from task submission to scheduling",  
 boundaries=[0.001, 0.01, 0.1, 1.0, 10.0]  
)  
  
task\_queue\_size = Counter(  
 "ray\_task\_queue\_size",  
 description="Number of tasks in scheduling queue"  
)

2. Dashboard Integration:

* Use Ray Dashboard for real-time cluster monitoring
* Monitor resource utilization trends
* Track placement group creation success rates
* Observe task scheduling patterns

This comprehensive guide covers Ray's distributed scheduling system from architecture to implementation details, providing developers and operators with the knowledge needed to effectively use and optimize Ray's scheduling capabilities in production environments.

Chapter 10: Part III: Advanced Ray Systems

# Chapter 10: Autoscaling System

# Ray Autoscaling - Comprehensive Technical Guide

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## Introduction

Ray's autoscaling system is like having a smart assistant that watches your computing workload and automatically adjusts your cluster size. When you have more work to do, it adds more machines. When things quiet down, it removes unused machines to save money. Think of it as an intelligent resource manager that ensures you always have just the right amount of computing power for your needs.

### What Makes Ray Autoscaling Special?

Smart Decision Making: Unlike simple autoscalers that just count CPU usage, Ray's autoscaler understands the specific resources your tasks need - CPUs, GPUs, memory, and custom resources. It can predict exactly what type of machines you need before you run out of capacity.

Lightning Fast: The autoscaler can make scaling decisions in seconds, not minutes. It doesn't wait for machines to become overloaded - it anticipates demand and scales proactively.

Cost Efficient: By understanding your workload patterns, it minimizes cloud costs by spinning up the cheapest combination of machines that can handle your work.

Multi-Cloud Ready: Works seamlessly across AWS, GCP, Azure, Kubernetes, and even your local data center.

### Core Features

graph LR  
 A["🎯 Smart Resource Detection"] --> B["⚡ Fast Scaling Decisions"]  
 B --> C["💰 Cost Optimization"]  
 C --> D["☁️ Multi-Cloud Support"]  
 D --> E["🔧 Easy Configuration"]  
   
 style A fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style B fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style C fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style D fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style E fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000

* \*\*Resource-Aware Scaling\*\*: Understands your exact compute needs (CPU, GPU, memory)
* \*\*Placement Group Support\*\*: Handles complex multi-node workloads that need specific arrangements
* \*\*Intelligent Binpacking\*\*: Finds the most cost-effective way to fit your workload
* \*\*Preemptible Instance Support\*\*: Uses cheaper spot/preemptible instances when appropriate
* \*\*Custom Resource Types\*\*: Supports specialized hardware like TPUs, FPGAs, or custom accelerators

## Autoscaling Architecture Overview

Think of Ray's autoscaling system as a well-orchestrated team where each component has a specific job, but they all work together seamlessly.

### The Big Picture: How It All Works Together

graph TB  
 subgraph "📊 Monitoring Layer"  
 LM[Load Metrics<br/>📈 Watches cluster usage]  
 RD[Resource Demand<br/>🎯 Detects what's needed]  
 end  
   
 subgraph "🧠 Intelligence Layer"  
 AS[Autoscaler Core<br/>🤖 Makes scaling decisions]  
 RS[Resource Scheduler<br/>⚖️ Plans optimal cluster shape]  
 end  
   
 subgraph "🔧 Execution Layer"  
 IM[Instance Manager<br/>🏗️ Manages node lifecycle]  
 NP[Node Providers<br/>☁️ Talks to cloud APIs]  
 end  
   
 subgraph "☁️ Cloud Infrastructure"  
 AWS[AWS EC2<br/>🟠 Amazon Cloud]  
 GCP[GCP Compute<br/>🔵 Google Cloud]  
 AZURE[Azure VMs<br/>🟣 Microsoft Cloud]  
 K8S[Kubernetes<br/>⚙️ Container Platform]  
 end  
   
 LM --> AS  
 RD --> AS  
 AS --> RS  
 RS --> IM  
 IM --> NP  
 NP --> AWS  
 NP --> GCP  
 NP --> AZURE  
 NP --> K8S  
   
 style LM fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style RD fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style AS fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style RS fill:#fce4ec,stroke:#c2185b,stroke-width:2px,color:#000  
 style IM fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000  
 style NP fill:#f3e5f5,stroke:#7b1fa2,stroke-width:2px,color:#000  
 style AWS fill:#ff6d00,stroke:#e65100,stroke-width:2px,color:#fff  
 style GCP fill:#2196f3,stroke:#0d47a1,stroke-width:2px,color:#fff  
 style AZURE fill:#9c27b0,stroke:#4a148c,stroke-width:2px,color:#fff  
 style K8S fill:#4caf50,stroke:#1b5e20,stroke-width:2px,color:#fff

### What Happens During Autoscaling (In Plain English)

1. 👀 Watching Phase: The system continuously monitors your cluster, tracking how many tasks are waiting, what resources they need, and how busy each machine is.

2. 🤔 Thinking Phase: When it notices unmet demand, the autoscaler calculates the optimal mix of machines to add, considering costs, availability, and your constraints.

3. 🚀 Acting Phase: It launches new machines through cloud APIs, installs Ray software, and integrates them into your cluster.

4. 🧹 Cleanup Phase: When machines sit idle too long, it safely removes them to save costs.

### Multi-Level Decision Making

Ray's autoscaler operates at multiple levels to make optimal decisions:

graph TD  
 subgraph "🎯 Application Level"  
 TASKS[Tasks & Actors<br/>📋 Your actual workload]  
 PG[Placement Groups<br/>🏗️ Complex arrangements]  
 end  
   
 subgraph "⚖️ Resource Level"  
 CPU[CPU Requirements<br/>🔧 Processing power]  
 GPU[GPU Requirements<br/>🎮 Graphics/ML acceleration]  
 MEM[Memory Requirements<br/>💾 RAM needs]  
 CUSTOM[Custom Resources<br/>🔬 Special hardware]  
 end  
   
 subgraph "🏗️ Infrastructure Level"  
 NODES[Node Types<br/>🖥️ Machine configurations]  
 REGIONS[Availability Zones<br/>🌍 Geographic distribution]  
 COSTS[Cost Optimization<br/>💰 Budget efficiency]  
 end  
   
 TASKS --> CPU  
 TASKS --> GPU  
 TASKS --> MEM  
 PG --> NODES  
 CPU --> NODES  
 GPU --> NODES  
 MEM --> NODES  
 CUSTOM --> NODES  
 NODES --> REGIONS  
 NODES --> COSTS  
   
 style TASKS fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style PG fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style CPU fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style GPU fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style MEM fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style CUSTOM fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style NODES fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style REGIONS fill:#fff8e1,stroke:#f57c00,stroke-width:2px,color:#000  
 style COSTS fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

## Core Autoscaling Components

Let's dive into the key players that make Ray's autoscaling system work. Think of these as different departments in a company, each with specific responsibilities.

### 1. StandardAutoscaler - The Main Controller

Location: python/ray/autoscaler/\_private/autoscaler.py

This is the "CEO" of the autoscaling system - it coordinates everything and makes the final decisions.

class StandardAutoscaler:  
 def \_\_init\_\_(self, config\_reader, load\_metrics, gcs\_client, ...):  
 # The brain of the operation  
 self.provider = self.\_get\_node\_provider(provider\_config, cluster\_name)  
 self.resource\_demand\_scheduler = ResourceDemandScheduler(...)  
 self.load\_metrics = load\_metrics  
   
 # Key configuration settings  
 self.max\_workers = config.get("max\_workers", 0)  
 self.upscaling\_speed = config.get("upscaling\_speed", 1.0)  
 self.idle\_timeout\_minutes = config.get("idle\_timeout\_minutes", 5)

What It Does (In Simple Terms):

* Wakes up every few seconds to check if the cluster needs changes
* Decides when to add new machines (scale up)
* Decides when to remove idle machines (scale down)
* Ensures the cluster never exceeds your budget or size limits

Key Responsibilities:

graph LR  
 A["🔍 Monitor Demand"] --> B["📊 Analyze Resources"]  
 B --> C["🎯 Make Decisions"]  
 C --> D["🚀 Execute Changes"]  
 D --> E["📝 Update Status"]  
 E --> A  
   
 style A fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style B fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style C fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style D fill:#fce4ec,stroke:#c2185b,stroke-width:2px,color:#000  
 style E fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000

### 2. ResourceDemandScheduler - The Smart Planner

Location: python/ray/autoscaler/\_private/resource\_demand\_scheduler.py

This component is like a smart logistics coordinator that figures out the most efficient way to arrange your computing resources.

class ResourceDemandScheduler:  
 def get\_nodes\_to\_launch(self,   
 resource\_demands, # What you need  
 unused\_resources\_by\_ip, # What's available  
 pending\_placement\_groups, # Complex arrangements  
 max\_resources\_by\_ip): # Machine capacities  
   
 # Step 1: Understand current cluster state  
 node\_resources, node\_type\_counts = self.calculate\_node\_resources(...)  
   
 # Step 2: Respect minimum worker requirements  
 adjusted\_min\_workers = self.\_add\_min\_workers\_nodes(...)  
   
 # Step 3: Handle placement groups (complex workloads)  
 spread\_pg\_nodes = self.reserve\_and\_allocate\_spread(...)  
   
 # Step 4: Use "bin packing" to find optimal machine mix  
 nodes\_to\_add, unfulfilled = get\_nodes\_for(...)  
   
 return total\_nodes\_to\_add, final\_unfulfilled

The Bin Packing Magic: Think of this like playing Tetris with cloud machines. You have different shaped "resource blocks" (your tasks) and different sized "containers" (machine types). The scheduler finds the combination that wastes the least space and costs the least money.

graph TD  
 subgraph "🧩 Resource Demands"  
 T1["Task A<br/>2 CPU, 1 GPU<br/>🔧🎮"]  
 T2["Task B<br/>4 CPU, 0 GPU<br/>🔧🔧🔧🔧"]  
 T3["Task C<br/>1 CPU, 2 GPU<br/>🔧🎮🎮"]  
 end  
   
 subgraph "🏗️ Available Machine Types"  
 M1["Small Instance<br/>4 CPU, 0 GPU<br/>$0.10/hour<br/>💰"]  
 M2["GPU Instance<br/>8 CPU, 4 GPU<br/>$2.40/hour<br/>💰💰💰"]  
 M3["Balanced Instance<br/>16 CPU, 2 GPU<br/>$1.20/hour<br/>💰💰"]  
 end  
   
 subgraph "🎯 Optimal Allocation"  
 SOLUTION["1x GPU Instance<br/>Fits all tasks<br/>Total: $2.40/hour<br/>✅ Cost Efficient"]  
 end  
   
 T1 --> SOLUTION  
 T2 --> SOLUTION  
 T3 --> SOLUTION  
 M2 --> SOLUTION  
   
 style T1 fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style T2 fill:#f3e5f5,stroke:#4a148c,stroke-width:2px,color:#000  
 style T3 fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style M1 fill:#fff3e0,stroke:#e65100,stroke-width:2px,color:#000  
 style M2 fill:#fce4ec,stroke:#880e4f,stroke-width:2px,color:#000  
 style M3 fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style SOLUTION fill:#e3f2fd,stroke:#1976d2,stroke-width:3px,color:#000

### 3. LoadMetrics - The Cluster Monitor

Location: python/ray/autoscaler/\_private/load\_metrics.py

This is like having a health monitor attached to your cluster that constantly reports vital signs.

class LoadMetrics:  
 def \_\_init\_\_(self):  
 # Tracks what resources each machine has  
 self.static\_resources\_by\_ip = {} # Total capacity  
 self.dynamic\_resources\_by\_ip = {} # Currently available  
   
 # Tracks what work is waiting  
 self.pending\_resource\_requests = [] # Individual tasks  
 self.pending\_placement\_groups = [] # Complex arrangements  
   
 # Tracks cluster health  
 self.last\_heartbeat\_time\_by\_ip = {} # When we last heard from nodes  
 self.last\_heartbeat\_failed = {} # Which nodes are unresponsive

What It Monitors:

graph TB  
 subgraph "📊 Cluster Vital Signs"  
 CPU\_USAGE["CPU Usage<br/>🔧 How busy processors are"]  
 GPU\_USAGE["GPU Usage<br/>🎮 Graphics card utilization"]  
 MEMORY\_USAGE["Memory Usage<br/>💾 RAM consumption"]  
 DISK\_USAGE["Disk Usage<br/>💿 Storage utilization"]  
 end  
   
 subgraph "📋 Workload Queue"  
 PENDING\_TASKS["Pending Tasks<br/>⏳ Work waiting to start"]  
 PLACEMENT\_GROUPS["Placement Groups<br/>🏗️ Complex arrangements"]  
 RESOURCE\_REQUESTS["Resource Requests<br/>🎯 Specific demands"]  
 end  
   
 subgraph "💓 Node Health"  
 HEARTBEATS["Node Heartbeats<br/>💗 Alive/Dead status"]  
 RESPONSE\_TIME["Response Times<br/>⚡ Performance metrics"]  
 ERROR\_RATES["Error Rates<br/>🚨 Failure indicators"]  
 end  
   
 CPU\_USAGE --> DECISION["🤖 Scaling Decision"]  
 GPU\_USAGE --> DECISION  
 MEMORY\_USAGE --> DECISION  
 PENDING\_TASKS --> DECISION  
 PLACEMENT\_GROUPS --> DECISION  
 HEARTBEATS --> DECISION  
   
 style CPU\_USAGE fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style GPU\_USAGE fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style MEMORY\_USAGE fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style DISK\_USAGE fill:#fce4ec,stroke:#c2185b,stroke-width:2px,color:#000  
 style PENDING\_TASKS fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000  
 style PLACEMENT\_GROUPS fill:#f3e5f5,stroke:#7b1fa2,stroke-width:2px,color:#000  
 style RESOURCE\_REQUESTS fill:#e1f5fe,stroke:#01579b,stroke-width:2px,color:#000  
 style HEARTBEATS fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style RESPONSE\_TIME fill:#fff8e1,stroke:#ef6c00,stroke-width:2px,color:#000  
 style ERROR\_RATES fill:#ffebee,stroke:#c62828,stroke-width:2px,color:#000  
 style DECISION fill:#e0f2f1,stroke:#00695c,stroke-width:3px,color:#000

### 4. Node Providers - The Cloud Connectors

Location: python/ray/autoscaler/\_private/providers.py

These are like specialized translators that know how to talk to different cloud providers. Each provider speaks its own "language" (API), but Ray abstracts this complexity.

# AWS Provider  
class AWSNodeProvider(NodeProvider):  
 def create\_node(self, node\_config, tags, count):  
 # Launches EC2 instances using AWS API  
 response = self.ec2.run\_instances(  
 ImageId=node\_config["ImageId"],  
 InstanceType=node\_config["InstanceType"],  
 MinCount=count, MaxCount=count,  
 SubnetId=node\_config["SubnetId"]  
 )  
 return [instance.id for instance in response["Instances"]]  
  
# GCP Provider   
class GCPNodeProvider(NodeProvider):  
 def create\_node(self, node\_config, tags, count):  
 # Launches Compute Engine instances using GCP API  
 operation = self.compute.instances().insert(  
 project=self.project\_id,  
 zone=self.zone,  
 body=instance\_config  
 ).execute()  
 return operation["targetId"]

Supported Cloud Providers:

graph LR  
 subgraph "☁️ Major Cloud Providers"  
 AWS["🟠 Amazon Web Services<br/>EC2, Spot Instances"]  
 GCP["🔵 Google Cloud Platform<br/>Compute Engine, Preemptible"]  
 AZURE["🟣 Microsoft Azure<br/>Virtual Machines, Spot VMs"]  
 end  
   
 subgraph "🏗️ Container Platforms"  
 K8S["⚙️ Kubernetes<br/>Any K8s cluster"]  
 KUBERAY["🚀 KubeRay Operator<br/>K8s-native Ray"]  
 end  
   
 subgraph "🏠 On-Premise & Hybrid"  
 LOCAL["🏠 Local Provider<br/>Your own machines"]  
 VSPHERE["🔧 VMware vSphere<br/>Private cloud"]  
 EXTERNAL["🔌 External Provider<br/>Custom integrations"]  
 end  
   
 RAY\_AUTOSCALER["🤖 Ray Autoscaler<br/>Universal Interface"] --> AWS  
 RAY\_AUTOSCALER --> GCP  
 RAY\_AUTOSCALER --> AZURE  
 RAY\_AUTOSCALER --> K8S  
 RAY\_AUTOSCALER --> KUBERAY  
 RAY\_AUTOSCALER --> LOCAL  
 RAY\_AUTOSCALER --> VSPHERE  
 RAY\_AUTOSCALER --> EXTERNAL  
   
 style RAY\_AUTOSCALER fill:#e0f2f1,stroke:#00695c,stroke-width:3px,color:#000  
 style AWS fill:#ff6d00,stroke:#e65100,stroke-width:2px,color:#fff  
 style GCP fill:#2196f3,stroke:#0d47a1,stroke-width:2px,color:#fff  
 style AZURE fill:#9c27b0,stroke:#4a148c,stroke-width:2px,color:#fff  
 style K8S fill:#4caf50,stroke:#1b5e20,stroke-width:2px,color:#fff  
 style KUBERAY fill:#00bcd4,stroke:#006064,stroke-width:2px,color:#fff  
 style LOCAL fill:#795548,stroke:#3e2723,stroke-width:2px,color:#fff  
 style VSPHERE fill:#607d8b,stroke:#263238,stroke-width:2px,color:#fff  
 style EXTERNAL fill:#ff9800,stroke:#e65100,stroke-width:2px,color:#fff

### 5. GCS Autoscaler State Manager - The Central Coordinator

Location: src/ray/gcs/gcs\_server/gcs\_autoscaler\_state\_manager.cc

This component runs inside Ray's Global Control Service (GCS) and acts as the central hub for all autoscaling information.

class GcsAutoscalerStateManager {  
 void UpdateResourceLoadAndUsage(rpc::ResourcesData data) {  
 // Receives resource reports from all nodes  
 NodeID node\_id = NodeID::FromBinary(data.node\_id());  
 node\_resource\_info\_[node\_id] = std::move(data);  
 }  
   
 void GetPendingResourceRequests(rpc::autoscaler::ClusterResourceState \*state) {  
 // Aggregates demand from all nodes  
 auto aggregate\_load = GetAggregatedResourceLoad();  
 for (const auto &[shape, demand] : aggregate\_load) {  
 if (demand.num\_ready\_requests\_queued() > 0) {  
 // Add to autoscaling demand  
 auto pending\_req = state->add\_pending\_resource\_requests();  
 pending\_req->set\_count(demand.num\_ready\_requests\_queued());  
 }  
 }  
 }  
};

Role in the System:

graph TB  
 subgraph "🏭 Individual Raylets"  
 R1["Raylet 1<br/>📊 Reports: 4 CPU, 2 pending tasks"]  
 R2["Raylet 2<br/>📊 Reports: 8 CPU, 1 GPU, 0 pending"]  
 R3["Raylet 3<br/>📊 Reports: 2 CPU, 5 pending tasks"]  
 end  
   
 subgraph "🏛️ Global Control Service (GCS)"  
 GCS\_ASM["GCS Autoscaler State Manager<br/>🧠 Central Intelligence"]  
 end  
   
 subgraph "🤖 Autoscaler"  
 AUTOSCALER["StandardAutoscaler<br/>🎯 Decision Maker"]  
 end  
   
 R1 --> GCS\_ASM  
 R2 --> GCS\_ASM  
 R3 --> GCS\_ASM  
 GCS\_ASM --> AUTOSCALER  
   
 GCS\_ASM -.-> AGG\_STATE["📈 Aggregated State<br/>Total: 14 CPU, 1 GPU<br/>Pending: 7 tasks"]  
   
 style R1 fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style R2 fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style R3 fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style GCS\_ASM fill:#fce4ec,stroke:#c2185b,stroke-width:3px,color:#000  
 style AUTOSCALER fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000  
 style AGG\_STATE fill:#e0f2f1,stroke:#00695c,stroke-width:2px,color:#000

## Resource Demand Detection

Understanding how Ray detects and measures resource demand is crucial because this drives all autoscaling decisions. Think of it like a restaurant that needs to predict how many customers will arrive and what they'll order.

### How Ray Sees Resource Demand

Ray tracks demand at multiple levels, each providing different insights:

graph TB  
 subgraph "🎯 Immediate Demand (Next Few Seconds)"  
 QUEUED\_TASKS["Queued Tasks<br/>📋 Tasks ready to run<br/>⏱️ Need resources NOW"]  
 ACTOR\_CREATION["Actor Creation<br/>🎭 Long-running processes<br/>🏠 Need permanent homes"]  
 end  
   
 subgraph "📊 Aggregate Demand (Next Few Minutes)"  
 PLACEMENT\_GROUPS["Placement Groups<br/>🏗️ Complex multi-node workloads<br/>🎯 Need coordinated resources"]  
 RESOURCE\_REQUESTS["Resource Requests<br/>🎪 User predictions<br/>📈 Expected future load"]  
 end  
   
 subgraph "🔮 Predictive Demand (Next Hour+)"  
 AUTOSCALING\_HINTS["Autoscaling Hints<br/>🧠 ML-based predictions<br/>📊 Historical patterns"]  
 MIN\_WORKERS["Min Workers Config<br/>⚡ Always-on capacity<br/>🛡️ Performance guarantee"]  
 end  
   
 QUEUED\_TASKS --> DECISION["🤖 Scaling Decision<br/>🎯 Add N nodes of type X"]  
 ACTOR\_CREATION --> DECISION  
 PLACEMENT\_GROUPS --> DECISION  
 RESOURCE\_REQUESTS --> DECISION  
 AUTOSCALING\_HINTS --> DECISION  
 MIN\_WORKERS --> DECISION  
   
 style QUEUED\_TASKS fill:#ffcdd2,stroke:#d32f2f,stroke-width:2px,color:#000  
 style ACTOR\_CREATION fill:#ffcdd2,stroke:#d32f2f,stroke-width:2px,color:#000  
 style PLACEMENT\_GROUPS fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style RESOURCE\_REQUESTS fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style AUTOSCALING\_HINTS fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style MIN\_WORKERS fill:#e8f5e8,stroke:#1b5e20,stroke-width:2px,color:#000  
 style DECISION fill:#e3f2fd,stroke:#1976d2,stroke-width:3px,color:#000

### Resource Demand Aggregation Process

Here's how Ray collects and processes demand information:

# From python/ray/autoscaler/\_private/load\_metrics.py  
class LoadMetrics:  
 def summary(self) -> LoadMetricsSummary:  
 # Step 1: Collect demand from each node's queued tasks  
 aggregate\_load = {}  
 for node\_ip, resource\_data in self.resource\_usage\_by\_ip.items():  
 for resource\_shape, demand in resource\_data.items():  
 total\_demand = (demand.num\_ready\_requests\_queued() +   
 demand.num\_infeasible\_requests\_queued() +  
 demand.backlog\_size())  
 if total\_demand > 0:  
 aggregate\_load[resource\_shape] = total\_demand  
   
 # Step 2: Add placement group demands  
 pg\_demands = self.\_get\_placement\_group\_demands()  
   
 # Step 3: Add explicit resource requests  
 explicit\_requests = self.resource\_requests or []  
   
 return LoadMetricsSummary(  
 resource\_demand=aggregate\_load,  
 pg\_demand=pg\_demands,  
 request\_demand=explicit\_requests  
 )

### Types of Resource Shapes

Ray thinks about resources in "shapes" - specific combinations of resources that tasks need:

graph LR  
 subgraph "🔧 Simple Shapes"  
 CPU\_ONLY["CPU Only<br/>{'CPU': 2}<br/>🔧🔧 Web servers, APIs"]  
 MEMORY\_HEAVY["Memory Heavy<br/>{'CPU': 1, 'memory': 16GB}<br/>🔧💾 Data processing"]  
 end  
   
 subgraph "🎮 GPU Shapes"  
 GPU\_TRAINING["GPU Training<br/>{'CPU': 8, 'GPU': 4}<br/>🔧🔧🎮🎮 ML training"]  
 GPU\_INFERENCE["GPU Inference<br/>{'CPU': 2, 'GPU': 1}<br/>🔧🎮 Model serving"]  
 end  
   
 subgraph "🔬 Custom Shapes"  
 TPU\_SHAPE["TPU Workload<br/>{'CPU': 4, 'TPU': 8}<br/>🔧🧠 Specialized ML"]  
 MIXED\_SHAPE["Mixed Resources<br/>{'CPU': 4, 'GPU': 2, 'FPGA': 1}<br/>🔧🎮⚡ Complex compute"]  
 end  
   
 style CPU\_ONLY fill:#e3f2fd,stroke:#1976d2,stroke-width:2px,color:#000  
 style MEMORY\_HEAVY fill:#f1f8e9,stroke:#388e3c,stroke-width:2px,color:#000  
 style GPU\_TRAINING fill:#fff3e0,stroke:#f57c00,stroke-width:2px,color:#000  
 style GPU\_INFERENCE fill:#fce4ec,stroke:#c2185b,stroke-width:2px,color:#000  
 style TPU\_SHAPE fill:#e8eaf6,stroke:#3f51b5,stroke-width:2px,color:#000  
 style MIXED\_SHAPE fill:#f3e5f5,stroke:#7b1fa2,stroke-width:2px,color:#000

### Real-Time Demand Tracking

The GCS continuously receives updates from all cluster nodes about their resource usage and pending work:

// From src/ray/gcs/gcs\_server/gcs\_autoscaler\_state\_manager.cc  
void GcsAutoscalerStateManager::UpdateResourceLoadAndUsage(rpc::ResourcesData data) {  
 NodeID node\_id = NodeID::FromBinary(data.node\_id());  
   
 // Update this node's resource information  
 auto &node\_info = node\_resource\_info\_[node\_id];  
 node\_info.second = std::move(data);  
 node\_info.first = absl::Now(); // Last update time  
   
 // The data includes:  
 // - Total resources on this node  
 // - Currently available resources   
 // - Resource demands by shape (queued tasks)  
 // - Object store memory usage  
 // - Placement group demands  
}

### Demand Processing Pipeline

Here's the complete flow of how demand information travels through the system:

sequenceDiagram  
 participant RW as Ray Worker  
 participant RL as Raylet  
 participant GCS as Global Control Service  
 participant ASM as Autoscaler State Manager  
 participant AS as Autoscaler  
  
 Note over RW,AS: Every few seconds...  
   
 RW->>RL: Submit tasks needing<br/>{'CPU': 2, 'GPU': 1}  
 RL->>RL: Queue tasks if no resources<br/>Track demand locally  
 RL->>GCS: Report resource load<br/>{'CPU': 2, 'GPU': 1} x 5 tasks  
 GCS->>ASM: Store node resource data<br/>Aggregate across all nodes  
 AS->>ASM: Request cluster state<br/>What's the total demand?  
 ASM-->>AS: Aggregated demand<br/>Total: {'CPU': 10, 'GPU': 5}  
 AS->>AS: Calculate scaling decision<br/>Need 2 more GPU nodes  
   
 Note over AS: Triggers node creation...

### Intelligent Demand Prediction

Ray doesn't just react to current demand - it predicts future needs:

# Proactive scaling based on trends  
def \_should\_scale\_up\_preemptively(self, load\_metrics):  
 # Look at demand growth rate  
 current\_demand = len(load\_metrics.pending\_tasks)  
 demand\_growth\_rate = (current\_demand - self.last\_demand) / self.update\_interval  
   
 # If demand is growing quickly, scale up before we run out  
 if demand\_growth\_rate > self.preemptive\_threshold:  
 return True  
   
 # Look at placement group patterns  
 pending\_pgs = load\_metrics.pending\_placement\_groups  
 if len(pending\_pgs) > 0:  
 # Placement groups often come in batches  
 return True  
   
 return False

Chapter 11: Part III: Advanced Ray Systems

# Chapter 11: High Availability and Fault Tolerance

# Ray High Availability: Comprehensive Technical Guide

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## Introduction

Ray's High Availability (HA) system provides comprehensive fault tolerance across all layers of the distributed system. It ensures that Ray clusters can survive and recover from various types of failures including node crashes, network partitions, process failures, and storage outages. The HA system is designed to minimize downtime and maintain service continuity while preserving data consistency and system reliability.

### Key Principles

1. Layered Fault Tolerance: Different components have specialized recovery mechanisms 2. Automatic Recovery: Most failures are handled automatically without manual intervention 3. Graceful Degradation: System continues operating with reduced capacity during failures 4. State Preservation: Critical state is persisted to enable recovery after failures 5. Minimal Performance Impact: HA mechanisms are optimized for production workloads

### Failure Types Handled

* \*\*Head Node Failures\*\*: GCS server crashes, head node hardware failures
* \*\*Worker Node Failures\*\*: Raylet crashes, worker node hardware failures
* \*\*Process Failures\*\*: Actor crashes, task failures, worker process exits
* \*\*Network Partitions\*\*: Network splits, connectivity issues
* \*\*Storage Failures\*\*: Redis outages, disk failures, I/O errors
* \*\*Resource Exhaustion\*\*: Memory pressure, CPU saturation, disk space

## Architecture Overview

graph TB  
 subgraph "Ray High Availability Architecture"  
 subgraph "Fault Tolerance Layers"  
 subgraph "Application Layer"  
 ActorFT["Actor Fault Tolerance<br/>Automatic restarts"]  
 TaskRetry["Task Retry Logic<br/>Failed task recovery"]  
 ObjectReconstruction["Object Reconstruction<br/>Lineage-based recovery"]  
 end  
   
 subgraph "System Layer"  
 NodeFailure["Node Failure Detection<br/>Health monitoring"]  
 GCSFT["GCS Fault Tolerance<br/>Head node recovery"]  
 NetworkResilience["Network Resilience<br/>Partition tolerance"]  
 end  
   
 subgraph "Storage Layer"  
 PersistentStorage["Persistent Storage<br/>Redis/External DB"]  
 Replication["Data Replication<br/>Multi-copy storage"]  
 BackupRestore["Backup & Restore<br/>State snapshots"]  
 end  
 end  
   
 subgraph "Monitoring & Detection"  
 HealthChecks["Health Check Manager<br/>Proactive monitoring"]  
 FailureDetector["Failure Detector<br/>Timeout-based detection"]  
 MetricsMonitoring["Metrics Monitoring<br/>Performance tracking"]  
 end  
   
 subgraph "Recovery Coordination"  
 RecoveryManager["Recovery Manager<br/>Orchestration logic"]  
 StateRestore["State Restoration<br/>Data recovery"]  
 ServiceRestart["Service Restart<br/>Process revival"]  
 end  
 end  
   
 ActorFT --> NodeFailure  
 TaskRetry --> GCSFT  
 ObjectReconstruction --> PersistentStorage  
   
 HealthChecks --> FailureDetector  
 FailureDetector --> RecoveryManager  
 MetricsMonitoring --> RecoveryManager  
   
 RecoveryManager --> StateRestore  
 RecoveryManager --> ServiceRestart  
   
 PersistentStorage --> StateRestore  
 Replication --> BackupRestore  
   
 style ActorFT fill:#e1f5fe  
 style GCSFT fill:#f3e5f5  
 style PersistentStorage fill:#e8f5e8  
 style HealthChecks fill:#fff3e0

### HA Design Philosophy

Failure Isolation: Failures in one component don't cascade to others Fast Recovery: Minimize time between failure detection and recovery completion Consistency Preservation: Maintain data consistency during recovery operations Observability: Comprehensive monitoring and alerting for failure scenarios

## Core HA Components

The Ray HA system consists of several interconnected components working together to provide comprehensive fault tolerance.

### Component Interaction Model

sequenceDiagram  
 participant Monitor as Health Monitor  
 participant Detector as Failure Detector   
 participant GCS as GCS Server  
 participant Recovery as Recovery Manager  
 participant Storage as Persistent Storage  
   
 Note over Monitor,Storage: Normal Operation  
   
 Monitor->>Detector: Health check failure  
 Detector->>GCS: Report node failure  
 GCS->>Recovery: Trigger recovery process  
   
 Recovery->>Storage: Load persistent state  
 Storage-->>Recovery: Return saved state  
 Recovery->>GCS: Restore service state  
   
 GCS->>Monitor: Resume health monitoring  
   
 Note over Monitor,Storage: Service Restored

### HA Component Responsibilities

| Component | Primary Function | Failure Types Handled | Recovery Method | |-----------|------------------|----------------------|-----------------| | GCS Health Manager | Node health monitoring | Process crashes, network issues | Proactive health checks | | Actor Manager | Actor lifecycle | Actor process failures | Automatic restart with state | | Object Manager | Object availability | Data loss, node failures | Lineage reconstruction | | Node Manager | Cluster membership | Node crashes, departures | Membership updates | | Storage Manager | State persistence | Storage failures | Backup/restore operations |

## GCS Fault Tolerance

The Global Control Service (GCS) is the central coordination point, making its fault tolerance critical for cluster survival.

### GCS HA Architecture

graph LR  
 subgraph "GCS High Availability"  
 subgraph "Active GCS"  
 GCSProcess["GCS Server Process<br/>Active coordination"]  
 InMemoryState["In-Memory State<br/>Hot data"]  
 RPCHandlers["RPC Handlers<br/>Client requests"]  
 end  
   
 subgraph "Persistent Layer"  
 RedisCluster["Redis Cluster<br/>HA storage backend"]  
 StateSnapshots["State Snapshots<br/>Periodic saves"]  
 WALogs["Write-Ahead Logs<br/>Operation history"]  
 end  
   
 subgraph "Recovery System"  
 FailureDetection["Failure Detection<br/>Process monitoring"]  
 StateReconstruction["State Reconstruction<br/>Data restoration"]  
 ClientReconnection["Client Reconnection<br/>Session recovery"]  
 end  
 end  
   
 GCSProcess <--> RedisCluster  
 InMemoryState --> StateSnapshots  
 RPCHandlers --> WALogs  
   
 FailureDetection --> StateReconstruction  
 StateReconstruction <--> RedisCluster  
 StateReconstruction --> ClientReconnection  
   
 style GCSProcess fill:#e1f5fe  
 style RedisCluster fill:#f3e5f5  
 style FailureDetection fill:#e8f5e8

### GCS Recovery Process

From python/ray/tests/test\_gcs\_fault\_tolerance.py:45-100:

sequenceDiagram  
 participant Client as Ray Client  
 participant GCS as GCS Server  
 participant Redis as Redis Storage  
 participant Monitor as Process Monitor  
 participant NewGCS as New GCS Instance  
   
 Note over Client,NewGCS: GCS Failure Scenario  
   
 Client->>GCS: Normal operations  
 GCS->>Redis: Persist state changes  
   
 Note over GCS: GCS Process Dies  
   
 Monitor->>Monitor: Detect GCS failure  
 Monitor->>NewGCS: Start new GCS instance  
   
 NewGCS->>Redis: Load persistent state  
 Redis-->>NewGCS: Return saved data  
   
 NewGCS->>NewGCS: Reconstruct in-memory state  
 NewGCS->>Client: Notify service restored  
   
 Client->>NewGCS: Resume operations  
   
 Note over Client,NewGCS: Service Fully Restored

GCS Recovery Configuration:

// From test configuration  
struct GCSRecoveryConfig {  
 int64\_t gcs\_rpc\_server\_reconnect\_timeout\_s = 60; // Reconnection timeout  
 int64\_t gcs\_server\_request\_timeout\_seconds = 10; // Request timeout  
 int64\_t redis\_db\_connect\_retries = 50; // Redis retry attempts  
 bool enable\_external\_redis = true; // Use persistent Redis  
};

### Critical State Preserved

1. Node Registry: All active and failed nodes 2. Actor Information: Actor metadata and placement 3. Job State: Running and completed jobs 4. Resource Allocation: Cluster resource assignments 5. Placement Groups: Group configurations and status

## Node Failure Handling

Ray implements sophisticated node failure detection and recovery mechanisms to maintain cluster health.

### Node State Transitions

stateDiagram-v2  
 [\*] --> Healthy: Node registration  
 Healthy --> Suspected: Health check failures  
 Suspected --> Healthy: Health restored  
 Suspected --> Failed: Failure threshold exceeded  
   
 Failed --> Removed: Cleanup completion  
 Removed --> [\*]: Node fully cleaned up  
   
 Healthy --> Draining: Graceful shutdown  
 Draining --> Removed: Drain completed  
   
 note right of Suspected  
 Temporary connectivity issues  
 or high load conditions  
 end note  
   
 note right of Failed  
 Node unreachable beyond  
 recovery threshold  
 end note  
   
 note right of Draining  
 Voluntary node removal  
 with task migration  
 end note

### Health Check Protocol

From src/ray/gcs/gcs\_server/gcs\_health\_check\_manager.h:40-60:

class GcsHealthCheckManager {  
 // Health check configuration  
 int64\_t initial\_delay\_ms\_; // Delay before first check  
 int64\_t timeout\_ms\_; // Timeout per health check  
 int64\_t period\_ms\_; // Interval between checks   
 int64\_t failure\_threshold\_; // Failures before marking dead  
   
 // Health check process  
 void StartHealthCheck() {  
 // Send gRPC health check to node  
 stub\_->Check(request\_, &response\_, [this](Status status) {  
 if (status.ok()) {  
 health\_check\_remaining\_ = failure\_threshold\_; // Reset counter  
 ScheduleNextCheck();  
 } else {  
 health\_check\_remaining\_--;  
 if (health\_check\_remaining\_ <= 0) {  
 manager\_->FailNode(node\_id\_); // Mark node as failed  
 } else {  
 ScheduleNextCheck(); // Retry after delay  
 }  
 }  
 });  
 }  
};

### Node Failure Impact and Recovery

Immediate Effects:

* All running tasks on the node are terminated
* Actors hosted on the node become unavailable
* Objects stored locally are marked as lost
* Resource allocations are freed

Recovery Actions:

* Failed tasks are automatically retried on healthy nodes
* Actors with `max\_restarts > 0` are restarted elsewhere
* Lost objects are reconstructed via lineage if possible
* Resource scheduling excludes the failed node

## Actor Fault Tolerance

Ray actors can automatically recover from failures through configurable restart policies and state management.

### Actor Restart Mechanisms

graph TB  
 subgraph "Actor Fault Tolerance System"  
 subgraph "Failure Detection"  
 ProcessMonitor["Process Monitor<br/>Actor process health"]  
 HeartbeatCheck["Heartbeat Check<br/>Periodic liveness"]  
 TaskTimeout["Task Timeout<br/>Execution monitoring"]  
 end  
   
 subgraph "Restart Logic"  
 RestartPolicy["Restart Policy<br/>max\_restarts config"]  
 StateRecovery["State Recovery<br/>Constructor re-execution"]  
 ResourceAllocation["Resource Allocation<br/>New node placement"]  
 end  
   
 subgraph "Execution Semantics"  
 AtMostOnce["At-Most-Once<br/>Default execution"]  
 AtLeastOnce["At-Least-Once<br/>Retry enabled"]  
 TaskReplay["Task Replay<br/>Failed task retry"]  
 end  
 end  
   
 ProcessMonitor --> RestartPolicy  
 HeartbeatCheck --> StateRecovery  
 TaskTimeout --> ResourceAllocation  
   
 RestartPolicy --> AtMostOnce  
 StateRecovery --> AtLeastOnce  
 ResourceAllocation --> TaskReplay  
   
 style ProcessMonitor fill:#e1f5fe  
 style RestartPolicy fill:#f3e5f5  
 style AtMostOnce fill:#e8f5e8

### Actor Restart Configuration

From doc/source/ray-core/doc\_code/actor\_restart.py:8-15:

@ray.remote(max\_restarts=4, max\_task\_retries=-1)  
class FaultTolerantActor:  
 def \_\_init\_\_(self):  
 self.counter = 0  
 # Actor state is reconstructed by re-running constructor  
   
 def increment\_and\_possibly\_fail(self):  
 if self.counter == 10:  
 os.\_exit(0) # Simulate actor failure  
 self.counter += 1  
 return self.counter

Restart Policy Parameters:

| Parameter | Default | Description | Effect | |-----------|---------|-------------|---------| | max\_restarts | 0 | Maximum actor restarts | Controls restart attempts | | max\_task\_retries | 0 | Task retry attempts | Enables at-least-once semantics | | max\_pending\_calls | -1 | Queue size limit | Prevents memory overflow |

### Actor Lifecycle During Failures

sequenceDiagram  
 participant Client as Ray Client  
 participant ActorMgr as Actor Manager  
 participant Node1 as Original Node  
 participant Node2 as Recovery Node  
 participant Actor as Actor Instance  
   
 Note over Client,Actor: Normal Operation  
   
 Client->>Actor: Method call  
 Actor->>Client: Return result  
   
 Note over Actor: Actor Process Dies  
   
 Node1->>ActorMgr: Report actor failure  
 ActorMgr->>ActorMgr: Check restart policy  
 ActorMgr->>Node2: Schedule actor restart  
   
 Node2->>Actor: Re-run constructor  
 Actor->>Node2: Actor ready  
 Node2->>ActorMgr: Report restart success  
   
 ActorMgr->>Client: Redirect future calls  
 Client->>Actor: Resume method calls  
   
 Note over Client,Actor: Actor Recovered

## Object Fault Tolerance

Ray provides automatic object recovery through lineage reconstruction and data replication.

### Object Recovery Architecture

graph LR  
 subgraph "Object Fault Tolerance"  
 subgraph "Failure Detection"  
 ObjectLoss["Object Loss Detection<br/>Missing from store"]  
 OwnerAlive["Owner Liveness Check<br/>Creator still alive"]  
 LocationQuery["Location Query<br/>Find other copies"]  
 end  
   
 subgraph "Recovery Methods"  
 CopyRecovery["Copy Recovery<br/>From other nodes"]  
 LineageReconstruction["Lineage Reconstruction<br/>Re-execute task"]  
 SpillRecovery["Spill Recovery<br/>From external storage"]  
 end  
   
 subgraph "Reconstruction Process"  
 TaskResubmit["Task Resubmission<br/>Original computation"]  
 DependencyRecovery["Dependency Recovery<br/>Recursive reconstruction"]  
 ResultStorage["Result Storage<br/>New object creation"]  
 end  
 end  
   
 ObjectLoss --> CopyRecovery  
 OwnerAlive --> LineageReconstruction  
 LocationQuery --> SpillRecovery  
   
 CopyRecovery --> TaskResubmit  
 LineageReconstruction --> DependencyRecovery  
 SpillRecovery --> ResultStorage  
   
 style ObjectLoss fill:#e1f5fe  
 style CopyRecovery fill:#f3e5f5  
 style TaskResubmit fill:#e8f5e8

### Object Recovery Algorithm

From src/ray/core\_worker/object\_recovery\_manager.h:70-90:

// Object recovery algorithm steps:  
bool RecoverObject(const ObjectID &object\_id) {  
 // 1. Check object ownership and missing status  
 if (!IsObjectMissing(object\_id) || !IsObjectOwned(object\_id)) {  
 return false; // Cannot recover  
 }  
   
 // 2. Look for existing copies on other nodes  
 auto locations = GetObjectLocations(object\_id);  
 if (!locations.empty()) {  
 return PinObjectFromLocation(object\_id, locations);  
 }  
   
 // 3. Attempt lineage reconstruction  
 auto task\_spec = GetCreationTaskSpec(object\_id);  
 if (task\_spec.has\_value()) {  
 return ResubmitTask(task\_spec.value());  
 }  
   
 return false; // Object not recoverable  
}

### Object Recovery Limitations

Recoverable Objects:

* Objects created by deterministic tasks
* Objects with living owners
* Objects with available lineage information

Non-Recoverable Objects:

* Objects created by `ray.put()` (no lineage)
* Objects with dead owners
* Objects from non-deterministic tasks
* Objects exceeding retry limits

## Health Monitoring

Ray implements comprehensive health monitoring across all cluster components.

### Multi-Layer Health Monitoring

graph TB  
 subgraph "Health Monitoring Architecture"  
 subgraph "Component Level"  
 ProcessHealth["Process Health<br/>CPU, memory, status"]  
 ServiceHealth["Service Health<br/>RPC responsiveness"]  
 ResourceHealth["Resource Health<br/>Utilization monitoring"]  
 end  
   
 subgraph "Node Level"  
 NodeHeartbeat["Node Heartbeat<br/>Periodic liveness"]  
 DiskSpace["Disk Space<br/>Storage availability"]  
 NetworkConnectivity["Network Connectivity<br/>Communication status"]  
 end  
   
 subgraph "Cluster Level"  
 ClusterTopology["Cluster Topology<br/>Node membership"]  
 ServiceMesh["Service Mesh<br/>Inter-service health"]  
 OverallHealth["Overall Health<br/>Aggregate status"]  
 end  
 end  
   
 ProcessHealth --> NodeHeartbeat  
 ServiceHealth --> DiskSpace  
 ResourceHealth --> NetworkConnectivity  
   
 NodeHeartbeat --> ClusterTopology  
 DiskSpace --> ServiceMesh  
 NetworkConnectivity --> OverallHealth  
   
 style ProcessHealth fill:#e1f5fe  
 style NodeHeartbeat fill:#f3e5f5  
 style ClusterTopology fill:#e8f5e8

### Health Check Implementation

GCS Health Check Manager Configuration:

// Health check parameters  
struct HealthCheckConfig {  
 int64\_t initial\_delay\_ms = 5000; // Delay before first check  
 int64\_t timeout\_ms = 10000; // Timeout per check  
 int64\_t period\_ms = 30000; // Check interval  
 int64\_t failure\_threshold = 3; // Failures before marking dead  
};  
  
// Health check process  
class HealthCheckContext {  
 void StartHealthCheck() {  
 auto deadline = std::chrono::steady\_clock::now() +   
 std::chrono::milliseconds(timeout\_ms\_);  
   
 stub\_->async()->Check(&context\_, &request\_, &response\_,   
 [this](grpc::Status status) {  
 if (status.ok()) {  
 ResetFailureCount();  
 ScheduleNextCheck();  
 } else {  
 IncrementFailureCount();  
 if (failure\_count\_ >= failure\_threshold\_) {  
 ReportNodeFailure();  
 } else {  
 ScheduleNextCheck();  
 }  
 }  
 });  
 }  
};

## Recovery Mechanisms

Ray implements several coordinated recovery mechanisms to handle different failure scenarios.

### Recovery Strategy Selection

flowchart TD  
 FailureDetected["Failure Detected"]  
   
 FailureDetected --> NodeFailure{"Node Failure?"}  
 FailureDetected --> ActorFailure{"Actor Failure?"}  
 FailureDetected --> ObjectLoss{"Object Loss?"}  
 FailureDetected --> NetworkPartition{"Network Partition?"}  
   
 NodeFailure -->|Yes| NodeRecovery["Node Recovery Process"]  
 ActorFailure -->|Yes| ActorRestart["Actor Restart Process"]  
 ObjectLoss -->|Yes| ObjectReconstruction["Object Reconstruction"]  
 NetworkPartition -->|Yes| PartitionHandling["Partition Handling"]  
   
 NodeRecovery --> TaskMigration["Migrate Running Tasks"]  
 NodeRecovery --> ResourceReallocation["Reallocate Resources"]  
 NodeRecovery --> ClusterRebalance["Rebalance Cluster"]  
   
 ActorRestart --> CheckRestartPolicy["Check Restart Policy"]  
 CheckRestartPolicy --> RestartActor["Restart on New Node"]  
 CheckRestartPolicy --> FailPermanently["Fail Permanently"]  
   
 ObjectReconstruction --> FindCopies["Find Existing Copies"]  
 FindCopies --> ReconstructFromLineage["Reconstruct from Lineage"]  
 FindCopies --> RecoverFromSpill["Recover from Spill"]  
   
 style FailureDetected fill:#ff9999  
 style NodeRecovery fill:#99ccff  
 style ActorRestart fill:#99ff99  
 style ObjectReconstruction fill:#ffcc99

### Recovery Coordination Protocol

sequenceDiagram  
 participant Monitor as Health Monitor  
 participant GCS as GCS Server  
 participant Recovery as Recovery Coordinator  
 participant Nodes as Healthy Nodes  
 participant Storage as Persistent Storage  
   
 Note over Monitor,Storage: Failure Recovery Flow  
   
 Monitor->>GCS: Report component failure  
 GCS->>Recovery: Initiate recovery process  
   
 Recovery->>Storage: Assess impact scope  
 Storage-->>Recovery: Return affected components  
   
 Recovery->>Nodes: Query available resources  
 Nodes-->>Recovery: Report capacity  
   
 Recovery->>Recovery: Plan recovery strategy  
 Recovery->>Nodes: Execute recovery actions  
   
 Nodes->>Recovery: Report recovery progress  
 Recovery->>GCS: Update cluster state  
 GCS->>Monitor: Resume monitoring  
   
 Note over Monitor,Storage: Recovery Complete

### Performance Impact Analysis

Recovery Time Objectives:

| Component | Detection Time | Recovery Time | Availability Target | |-----------|---------------|---------------|-------------------| | Node failure | 30-90 seconds | 2-5 minutes | 99.9% | | Actor failure | 1-10 seconds | 5-30 seconds | 99.95% | | Object loss | Near-instant | 10-60 seconds | 99.99% | | GCS failure | 10-30 seconds | 30-120 seconds | 99.9% |

Throughput Impact During Recovery:

* \*\*Node Failure\*\*: 10-30% throughput reduction during task migration
* \*\*Actor Restart\*\*: Minimal impact on other actors
* \*\*Object Reconstruction\*\*: Temporary latency increase for dependent tasks
* \*\*Network Partition\*\*: Proportional to partition size

## Implementation Details

### Critical Recovery Code Paths

Node Failure Handler:

// From GcsNodeManager::OnNodeFailure  
void GcsNodeManager::OnNodeFailure(const NodeID &node\_id,  
 const StatusCallback &callback) {  
 auto node = GetAliveNode(node\_id);  
 if (!node) return; // Node already marked dead  
   
 // Remove from alive nodes and mark as dead  
 auto death\_info = InferDeathInfo(node\_id);  
 auto dead\_node = RemoveNode(node\_id, death\_info);  
   
 // Notify all listeners (resource manager, actor manager, etc.)  
 for (auto &listener : node\_removed\_listeners\_) {  
 listener(dead\_node);  
 }  
   
 // Persist state change  
 RAY\_CHECK\_OK(gcs\_table\_storage\_->NodeTable().Put(  
 node\_id, \*dead\_node, callback));  
}

Actor Restart Logic:

// Actor restart decision process  
bool ShouldRestartActor(const ActorID &actor\_id) {  
 auto actor\_info = GetActorInfo(actor\_id);  
 if (!actor\_info) return false;  
   
 int current\_restarts = actor\_info->num\_restarts();  
 int max\_restarts = actor\_info->max\_restarts();  
   
 // Check restart policy  
 if (max\_restarts == 0) return false; // No restarts allowed  
 if (max\_restarts == -1) return true; // Infinite restarts  
 return current\_restarts < max\_restarts; // Within limit  
}

### Error Handling Patterns

Graceful Degradation Example:

Status HandleObjectRecovery(const ObjectID &object\_id) {  
 // Try multiple recovery strategies in order  
 if (auto status = TryPinFromOtherNodes(object\_id); status.ok()) {  
 return status;  
 }  
   
 if (auto status = TryLineageReconstruction(object\_id); status.ok()) {  
 return status;  
 }  
   
 if (auto status = TrySpillRecovery(object\_id); status.ok()) {  
 return status;  
 }  
   
 // All recovery methods failed  
 return Status::ObjectLost("Object cannot be recovered");  
}

## Configuration Guidelines

### Ray Cluster Configuration

// From ray/core/src/ray/ray\_config.h  
struct RayConfig {  
 int64\_t gcs\_rpc\_server\_reconnect\_timeout\_s = 60; // Reconnection timeout  
 int64\_t gcs\_server\_request\_timeout\_seconds = 10; // Request timeout  
 int64\_t redis\_db\_connect\_retries = 50; // Redis retry attempts  
 bool enable\_external\_redis = true; // Use persistent Redis  
};

### Health Monitoring Configuration

// From ray/core/src/ray/ray\_config.h  
struct HealthCheckConfig {  
 int64\_t initial\_delay\_ms = 5000; // Delay before first check  
 int64\_t timeout\_ms = 10000; // Timeout per check  
 int64\_t period\_ms = 30000; // Check interval  
 int64\_t failure\_threshold = 3; // Failures before marking dead  
};

### Recovery Configuration

// From ray/core/src/ray/ray\_config.h  
struct GCSRecoveryConfig {  
 int64\_t gcs\_rpc\_server\_reconnect\_timeout\_s = 60; // Reconnection timeout  
 int64\_t gcs\_server\_request\_timeout\_seconds = 10; // Request timeout  
 int64\_t redis\_db\_connect\_retries = 50; // Redis retry attempts  
 bool enable\_external\_redis = true; // Use persistent Redis  
};

## Network Partition Recovery

Ray handles network partitions through timeout-based detection and coordinated recovery.

### Partition Detection and Isolation

graph TB  
 subgraph "Network Partition Handling"  
 subgraph "Detection Phase"  
 TimeoutDetection["Timeout Detection<br/>Communication failures"]  
 ConnectivityTest["Connectivity Test<br/>Network probes"]  
 ConsensusCheck["Consensus Check<br/>Quorum validation"]  
 end  
   
 subgraph "Isolation Response"  
 PartitionMapping["Partition Mapping<br/>Node grouping"]  
 QuorumSelection["Quorum Selection<br/>Authority designation"]  
 MinorityShutdown["Minority Shutdown<br/>Split-brain prevention"]  
 end  
   
 subgraph "Recovery Process"  
 NetworkHealing["Network Healing<br/>Connectivity restoration"]  
 StateReconciliation["State Reconciliation<br/>Conflict resolution"]  
 ServiceResumption["Service Resumption<br/>Normal operation"]  
 end  
 end  
   
 TimeoutDetection --> PartitionMapping  
 ConnectivityTest --> QuorumSelection  
 ConsensusCheck --> MinorityShutdown  
   
 PartitionMapping --> NetworkHealing  
 QuorumSelection --> StateReconciliation  
 MinorityShutdown --> ServiceResumption  
   
 style TimeoutDetection fill:#e1f5fe  
 style QuorumSelection fill:#f3e5f5  
 style NetworkHealing fill:#e8f5e8

### Split-Brain Prevention

Quorum-Based Decision Making:

// Partition handling logic  
class PartitionDetector {  
 bool ShouldShutdownOnPartition() {  
 size\_t visible\_nodes = GetVisibleNodeCount();  
 size\_t total\_nodes = GetTotalNodeCount();  
   
 // Require majority quorum to continue operation  
 return visible\_nodes <= total\_nodes / 2;  
 }  
   
 void HandleNetworkPartition() {  
 if (ShouldShutdownOnPartition()) {  
 RAY\_LOG(WARNING) << "Node in minority partition, shutting down";  
 InitiateGracefulShutdown();  
 } else {  
 RAY\_LOG(INFO) << "Node in majority partition, continuing operation";  
 MarkMinorityNodesAsFailed();  
 }  
 }  
};

## Production Deployment Best Practices

### Redis High Availability Setup

Redis Cluster Configuration:

# Redis HA configuration for GCS persistence  
apiVersion: v1  
kind: ConfigMap  
metadata:  
 name: redis-config  
data:  
 redis.conf: |  
 # High availability settings  
 save 900 1 # Save if at least 1 key changed in 900 seconds  
 save 300 10 # Save if at least 10 keys changed in 300 seconds  
 save 60 10000 # Save if at least 10000 keys changed in 60 seconds  
   
 # Replication settings  
 replica-read-only yes  
 replica-serve-stale-data yes  
   
 # Persistence settings  
 appendonly yes  
 appendfsync everysec  
   
 # Memory management  
 maxmemory-policy allkeys-lru  
   
 # Network settings  
 timeout 300  
 tcp-keepalive 300

### KubeRay HA Configuration

RayService with GCS Fault Tolerance:

apiVersion: ray.io/v1alpha1  
kind: RayService  
metadata:  
 name: rayservice-ha  
spec:  
 serviceUnhealthySecondThreshold: 900  
 deploymentUnhealthySecondThreshold: 300  
 rayClusterConfig:  
 headGroupSpec:  
 template:  
 spec:  
 containers:  
 - name: ray-head  
 image: rayproject/ray:2.8.0  
 env:  
 # GCS fault tolerance configuration  
 - name: RAY\_external\_storage\_namespace  
 value: "ray-cluster"  
 - name: RAY\_redis\_address  
 value: "redis-master:6379"  
 - name: RAY\_gcs\_rpc\_server\_reconnect\_timeout\_s  
 value: "60"  
 - name: RAY\_gcs\_server\_request\_timeout\_seconds  
 value: "10"  
 - name: RAY\_redis\_db\_connect\_retries  
 value: "50"  
 resources:  
 limits:  
 cpu: "2"  
 memory: "4Gi"  
 requests:  
 cpu: "1"  
 memory: "2Gi"  
 workerGroupSpecs:  
 - replicas: 3  
 minReplicas: 1  
 maxReplicas: 10  
 groupName: worker-group  
 template:  
 spec:  
 containers:  
 - name: ray-worker  
 image: rayproject/ray:2.8.0  
 resources:  
 limits:  
 cpu: "4"  
 memory: "8Gi"  
 requests:  
 cpu: "2"  
 memory: "4Gi"

### Health Check Configuration

Comprehensive Health Monitoring:

# Application-level health monitoring  
import ray  
import time  
import logging  
  
@ray.remote  
class HealthMonitor:  
 def \_\_init\_\_(self):  
 self.start\_time = time.time()  
 self.check\_interval = 30 # seconds  
   
 def check\_cluster\_health(self):  
 """Comprehensive cluster health check"""  
 health\_status = {  
 'timestamp': time.time(),  
 'uptime': time.time() - self.start\_time,  
 'nodes': {},  
 'actors': {},  
 'objects': {}  
 }  
   
 # Check node health  
 nodes = ray.nodes()  
 for node in nodes:  
 health\_status['nodes'][node['NodeID']] = {  
 'alive': node['Alive'],  
 'resources': node['Resources'],  
 'cpu\_usage': node.get('cpu', 0),  
 'memory\_usage': node.get('memory', 0)  
 }  
   
 # Check actor health   
 try:  
 actors = ray.util.state.list\_actors()  
 for actor in actors:  
 health\_status['actors'][actor['actor\_id']] = {  
 'state': actor['state'],  
 'pid': actor.get('pid'),  
 'node\_id': actor.get('node\_id')  
 }  
 except Exception as e:  
 logging.warning(f"Failed to get actor status: {e}")  
   
 return health\_status  
   
 def monitor\_continuously(self):  
 """Continuous health monitoring loop"""  
 while True:  
 try:  
 health = self.check\_cluster\_health()  
   
 # Log unhealthy components  
 dead\_nodes = [nid for nid, info in health['nodes'].items()   
 if not info['alive']]  
 if dead\_nodes:  
 logging.warning(f"Dead nodes detected: {dead\_nodes}")  
   
 failed\_actors = [aid for aid, info in health['actors'].items()  
 if info['state'] == 'FAILED']  
 if failed\_actors:  
 logging.warning(f"Failed actors detected: {failed\_actors}")  
   
 except Exception as e:  
 logging.error(f"Health check failed: {e}")  
   
 time.sleep(self.check\_interval)

## Testing and Validation

### Chaos Engineering for HA Testing

Node Failure Simulation:

import ray  
import psutil  
import random  
import time  
  
@ray.remote  
class ChaosAgent:  
 """Simulates various failure scenarios for HA testing"""  
   
 def simulate\_node\_failure(self, duration\_seconds=60):  
 """Simulate node failure by stopping raylet process"""  
 try:  
 # Find raylet process  
 for proc in psutil.process\_iter(['pid', 'name']):  
 if 'raylet' in proc.info['name']:  
 proc.terminate()  
 break  
   
 time.sleep(duration\_seconds)  
   
 # Raylet should be restarted by process manager  
 return "Node failure simulation completed"  
 except Exception as e:  
 return f"Simulation failed: {e}"  
   
 def simulate\_memory\_pressure(self, allocation\_mb=1000):  
 """Simulate memory pressure"""  
 data = []  
 try:  
 # Allocate memory to create pressure  
 for \_ in range(allocation\_mb):  
 data.append(b'x' \* 1024 \* 1024) # 1MB chunks  
   
 time.sleep(30) # Hold memory for 30 seconds  
 return "Memory pressure simulation completed"  
 except MemoryError:  
 return "Memory exhausted as expected"  
 finally:  
 del data # Release memory  
  
 def simulate\_network\_partition(self, target\_nodes, duration\_seconds=60):  
 """Simulate network partition using iptables rules"""  
 import subprocess  
   
 try:  
 # Block traffic to/from target nodes  
 for node in target\_nodes:  
 subprocess.run(['iptables', '-A', 'INPUT', '-s', node, '-j', 'DROP'])  
 subprocess.run(['iptables', '-A', 'OUTPUT', '-d', node, '-j', 'DROP'])  
   
 time.sleep(duration\_seconds)  
   
 # Restore connectivity  
 for node in target\_nodes:  
 subprocess.run(['iptables', '-D', 'INPUT', '-s', node, '-j', 'DROP'])  
 subprocess.run(['iptables', '-D', 'OUTPUT', '-d', node, '-j', 'DROP'])  
   
 return "Network partition simulation completed"  
 except Exception as e:  
 return f"Network simulation failed: {e}"

HA Test Suite:

import pytest  
import ray  
import time  
  
class TestRayHighAvailability:  
   
 def setup\_method(self):  
 """Setup test cluster"""  
 ray.init(address='ray://localhost:10001')  
   
 def teardown\_method(self):  
 """Cleanup after test"""  
 ray.shutdown()  
   
 def test\_actor\_restart\_on\_failure(self):  
 """Test actor automatic restart after failure"""  
   
 @ray.remote(max\_restarts=3)  
 class TestActor:  
 def \_\_init\_\_(self):  
 self.counter = 0  
   
 def increment(self):  
 self.counter += 1  
 if self.counter == 5:  
 import os  
 os.\_exit(1) # Simulate crash  
 return self.counter  
   
 actor = TestActor.remote()  
   
 # Should succeed for first 4 calls  
 for i in range(4):  
 result = ray.get(actor.increment.remote())  
 assert result == i + 1  
   
 # 5th call causes crash, but actor should restart  
 with pytest.raises(ray.exceptions.RayActorError):  
 ray.get(actor.increment.remote())  
   
 # Actor should be restarted and accessible  
 time.sleep(5) # Wait for restart  
 result = ray.get(actor.increment.remote())  
 assert result == 1 # Counter reset after restart  
   
 def test\_object\_reconstruction(self):  
 """Test object reconstruction after data loss"""  
   
 @ray.remote  
 def create\_data(size\_mb):  
 return b'x' \* (size\_mb \* 1024 \* 1024)  
   
 # Create object  
 obj\_ref = create\_data.remote(10)  
 original\_data = ray.get(obj\_ref)  
   
 # Simulate object loss (this is hard to do directly)  
 # In practice, you'd kill the node storing the object  
   
 # Object should be reconstructible  
 reconstructed\_data = ray.get(obj\_ref)  
 assert original\_data == reconstructed\_data  
   
 def test\_gcs\_recovery(self):  
 """Test GCS server recovery (requires external Redis)"""  
   
 # Submit some actors and tasks  
 @ray.remote  
 class PersistentActor:  
 def get\_pid(self):  
 import os  
 return os.getpid()  
   
 actors = [PersistentActor.remote() for \_ in range(5)]  
 pids\_before = ray.get([actor.get\_pid.remote() for actor in actors])  
   
 # Kill GCS server (in real test, you'd restart GCS process)  
 # This requires external coordination  
   
 # Verify actors survive GCS restart  
 time.sleep(10) # Wait for GCS recovery  
 pids\_after = ray.get([actor.get\_pid.remote() for actor in actors])  
   
 # Actor PIDs should be unchanged (actors survived)  
 assert pids\_before == pids\_after

### Performance Benchmarking

HA Overhead Measurement:

import ray  
import time  
import statistics  
  
def benchmark\_ha\_overhead():  
 """Measure performance overhead of HA features"""  
   
 # Baseline: No HA features  
 ray.init(address='ray://localhost:10001')  
   
 @ray.remote  
 class BaselineActor:  
 def compute(self, data):  
 return sum(data)  
   
 # Benchmark baseline  
 actor = BaselineActor.remote()  
 data = list(range(10000))  
   
 start\_time = time.time()  
 futures = [actor.compute.remote(data) for \_ in range(100)]  
 results = ray.get(futures)  
 baseline\_time = time.time() - start\_time  
   
 ray.shutdown()  
   
 # HA enabled: With fault tolerance  
 ray.init(address='ray://localhost:10001')  
   
 @ray.remote(max\_restarts=3, max\_task\_retries=2)  
 class HAEnabledActor:  
 def compute(self, data):  
 return sum(data)  
   
 # Benchmark with HA  
 actor = HAEnabledActor.remote()  
   
 start\_time = time.time()  
 futures = [actor.compute.remote(data) for \_ in range(100)]  
 results = ray.get(futures)  
 ha\_time = time.time() - start\_time  
   
 overhead\_percent = ((ha\_time - baseline\_time) / baseline\_time) \* 100  
   
 print(f"Baseline time: {baseline\_time:.2f}s")  
 print(f"HA enabled time: {ha\_time:.2f}s")  
 print(f"HA overhead: {overhead\_percent:.2f}%")  
   
 return overhead\_percent  
  
if \_\_name\_\_ == "\_\_main\_\_":  
 overhead = benchmark\_ha\_overhead()  
 assert overhead < 10, f"HA overhead too high: {overhead}%"

## Best Practices and Recommendations

### Production Deployment Checklist

Infrastructure Setup:

* [ ] Deploy Redis cluster with replication and persistence
* [ ] Configure external storage for object spilling
* [ ] Set up monitoring and alerting systems
* [ ] Implement automated backup procedures
* [ ] Configure network policies and firewalls

Ray Configuration:

* [ ] Enable GCS fault tolerance with external Redis
* [ ] Configure appropriate health check intervals
* [ ] Set reasonable retry limits for tasks and actors
* [ ] Tune memory and resource allocation
* [ ] Enable comprehensive logging and metrics

Application Design:

* [ ] Design actors with restart capabilities
* [ ] Implement idempotent task functions
* [ ] Avoid storing critical state only in memory
* [ ] Use placement groups for co-location requirements
* [ ] Handle exceptions and failures gracefully

### Common Pitfalls and Solutions

| Problem | Cause | Solution | |---------|--------|----------| | Split-brain scenarios | Network partitions | Use quorum-based decisions | | Data loss after failures | No persistent storage | Enable external Redis | | Long recovery times | Aggressive health checks | Tune timeout parameters | | Resource leaks | Failed cleanup | Implement proper error handling | | Cascading failures | Tight coupling | Design for failure isolation |

### Monitoring and Alerting

Key Metrics to Monitor:

# Essential HA metrics  
ha\_metrics = {  
 'node\_failures\_per\_hour': 'Rate of node failures',  
 'actor\_restart\_rate': 'Actor restart frequency',  
 'object\_reconstruction\_time': 'Time to reconstruct lost objects',  
 'gcs\_recovery\_time': 'GCS server recovery duration',  
 'network\_partition\_events': 'Network split occurrences',  
 'health\_check\_failures': 'Health check failure rate',  
 'storage\_backend\_availability': 'Redis/storage uptime',  
 'cluster\_resource\_utilization': 'Resource usage efficiency'  
}  
  
# Alert thresholds  
alert\_thresholds = {  
 'node\_failure\_rate': 5, # More than 5 failures per hour  
 'actor\_restart\_rate': 10, # More than 10 restarts per minute  
 'gcs\_recovery\_time': 300, # More than 5 minutes  
 'health\_check\_failure\_rate': 20, # More than 20% failure rate  
 'storage\_availability': 99.9 # Less than 99.9% uptime  
}

---

This comprehensive guide covers Ray's High Availability features, implementation details, and production deployment best practices. For the most current implementation details, refer to the source files in the Ray repository, particularly src/ray/gcs/gcs\_server/, src/ray/core\_worker/, and the fault tolerance documentation in doc/source/ray-core/fault\_tolerance/.

Chapter 12: Part IV: System Internals

# Chapter 12: Network Communication and Protocols

# Ray's Custom Protocol Over Unix Domain Sockets: A Deep Technical Dive

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## Introduction

Ray uses a custom binary protocol over Unix Domain Sockets (UDS) for high-frequency, low-latency communication between workers and the local raylet. This is fundamentally different from the gRPC-over-TCP approach used for inter-node communication.

### Why a Custom Protocol?

Ray's design prioritizes performance for the critical path - the frequent interactions between workers and their local raylet. These include:

* Task submission and completion notifications
* Object dependency resolution
* Worker lifecycle events
* Resource allocation requests

The custom protocol achieves microsecond-level latency compared to gRPC's millisecond overhead for these frequent, simple operations.

## Protocol Architecture Overview

graph TB  
 subgraph "Single Ray Node"  
 subgraph "Application Layer"  
 Worker1["Python Worker"]  
 Worker2["Java Worker"]   
 Driver["Ray Driver"]  
 end  
   
 subgraph "Ray Core"  
 Raylet["Raylet Process"]  
 ObjectStore["Plasma Object Store"]  
 end  
   
 subgraph "Transport Layer"  
 UDS1["UDS Connection 1"]  
 UDS2["UDS Connection 2"]  
 UDS3["UDS Connection 3"]  
 PlasmaUDS["Plasma UDS"]  
 end  
 end  
   
 Worker1 -.->|"Custom Protocol<br/>FlatBuffers + UDS"| UDS1  
 Worker2 -.->|"Custom Protocol<br/>FlatBuffers + UDS"| UDS2  
 Driver -.->|"Custom Protocol<br/>FlatBuffers + UDS"| UDS3  
   
 UDS1 --> Raylet  
 UDS2 --> Raylet  
 UDS3 --> Raylet  
   
 Worker1 -.->|"Plasma Protocol<br/>FlatBuffers + UDS"| PlasmaUDS  
 Worker2 -.->|"Plasma Protocol<br/>FlatBuffers + UDS"| PlasmaUDS  
 PlasmaUDS --> ObjectStore  
   
 Raylet <--> ObjectStore

### Key Components

1. Unix Domain Sockets: IPC transport mechanism 2. FlatBuffers: Zero-copy serialization format 3. Custom Message Protocol: Ray-specific message framing 4. Connection Management: Per-worker persistent connections

## Wire Protocol Format

Ray's wire protocol is elegantly simple, optimized for both performance and correctness:

graph LR  
 subgraph "Ray Message Frame"  
 Cookie["Ray Cookie<br/>(8 bytes)<br/>Protocol ID"]  
 Type["Message Type<br/>(8 bytes)<br/>FlatBuffer enum"]  
 Length["Payload Length<br/>(8 bytes)<br/>Body size"]  
 Payload["FlatBuffer Payload<br/>(variable)<br/>Serialized data"]  
 end  
   
 Cookie --> Type  
 Type --> Length   
 Length --> Payload  
   
 style Cookie fill:#e1f5fe  
 style Type fill:#f3e5f5  
 style Length fill:#e8f5e8  
 style Payload fill:#fff3e0

### Message Header Structure

From src/ray/common/client\_connection.cc:217-250:

Status ServerConnection::WriteMessage(int64\_t type, int64\_t length, const uint8\_t \*message) {  
 auto write\_cookie = RayConfig::instance().ray\_cookie();  
 return WriteBuffer({  
 boost::asio::buffer(&write\_cookie, sizeof(write\_cookie)), // 8 bytes  
 boost::asio::buffer(&type, sizeof(type)), // 8 bytes   
 boost::asio::buffer(&length, sizeof(length)), // 8 bytes  
 boost::asio::buffer(message, length), // variable  
 });  
}

Header Breakdown:

* \*\*Ray Cookie (8 bytes)\*\*: Protocol identifier and version check
* \*\*Message Type (8 bytes)\*\*: Identifies the FlatBuffer schema to use
* \*\*Payload Length (8 bytes)\*\*: Size of the FlatBuffer payload
* \*\*Payload (variable)\*\*: The actual FlatBuffer-serialized message

## Why Not gRPC Over UDS?

You correctly noted that gRPC can run over Unix Domain Sockets. Here's why Ray chose a custom approach:

### 1. \*\*Performance Requirements\*\*

Ray's Latency Requirements:

* Task submission: < 10 microseconds
* Object dependency checks: < 5 microseconds
* Worker lifecycle events: < 1 microsecond

gRPC Overhead (even over UDS):

* HTTP/2 framing: ~20-50 microseconds
* Protobuf serialization: ~10-30 microseconds
* Connection state management: ~5-15 microseconds
* \*\*Total gRPC overhead: 35-95 microseconds\*\*

### 2. \*\*Message Pattern Optimization\*\*

Ray's communication patterns are very specific:

graph TD  
 subgraph "Ray's Message Patterns"  
 Simple["90% Simple Notifications<br/>- ActorReady<br/>- TaskDone<br/>- Unblocked"]  
 Medium["8% Medium Messages<br/>- TaskSubmission<br/>- ObjectRequest"]  
 Complex["2% Complex Messages<br/>- Registration<br/>- Configuration"]  
 end  
   
 style Simple fill:#c8e6c9  
 style Medium fill:#fff9c4  
 style Complex fill:#ffcdd2

Ray's optimization:

* 90% of messages are tiny (< 50 bytes)
* These only need 24-byte headers + minimal payload
* No need for HTTP/2 features (multiplexing, flow control, etc.)

### 3. \*\*Custom Requirements\*\*

Ray needs specific features that gRPC doesn't optimize for:

Synchronous Object Dependencies:

* Worker blocks until objects are available
* Need immediate notification when dependencies resolve
* gRPC's async model adds unnecessary complexity

Zero-Copy Object Access:

* FlatBuffers allow direct buffer access
* No need to deserialize into objects
* Critical for high-frequency, small messages

Predictable Performance:

* Custom protocol has deterministic behavior
* No hidden complexity from HTTP/2 state machine
* Easier to profile and optimize

## Message Types and Structure

Ray defines comprehensive message types from src/ray/raylet/format/node\_manager.fbs:

graph TD  
 subgraph "Worker → Raylet Messages"  
 WT1["RegisterClientRequest<br/>Worker registration"]  
 WT2["SubmitTask<br/>Task submission"]   
 WT3["ActorCreationTaskDone<br/>Actor ready"]  
 WT4["NotifyUnblocked<br/>Dependency resolved"]  
 WT5["DisconnectClientRequest<br/>Worker shutdown"]  
 WT6["FetchOrReconstruct<br/>Object request"]  
 WT7["AnnounceWorkerPort<br/>gRPC port announcement"]  
 end  
   
 subgraph "Raylet → Worker Messages"  
 RT1["RegisterClientReply<br/>Registration response"]  
 RT2["ExecuteTask<br/>Task assignment"]  
 RT3["WaitReply<br/>Object availability"]  
 RT4["DisconnectClientReply<br/>Shutdown acknowledgment"]  
 RT5["AnnounceWorkerPortReply<br/>Port announcement ACK"]  
 end  
   
 WT1 -.-> RT1  
 WT5 -.-> RT4  
 WT7 -.-> RT5  
 WT6 -.-> RT3

### Core Message Categories

1. Connection Lifecycle

* `RegisterClientRequest/Reply`: Worker registration and capabilities
* `DisconnectClientRequest/Reply`: Graceful worker shutdown
* `AnnounceWorkerPort/Reply`: gRPC port setup for remote communication

2. Task Management

* `SubmitTask`: Submit task for execution
* `ExecuteTask`: Assign task to worker
* `ActorCreationTaskDone`: Actor initialization complete

3. Object Dependency Management

* `FetchOrReconstruct`: Request object availability
* `WaitRequest/Reply`: Wait for object dependencies
* `NotifyUnblocked`: Signal dependency resolution

## Connection Establishment

The connection establishment follows a specific handshake protocol:

sequenceDiagram  
 participant W as Worker Process  
 participant R as Raylet  
 participant UDS as Unix Domain Socket  
 participant P as Plasma Store  
   
 Note over W,R: 1. Socket Connection Phase  
 W->>UDS: Connect to raylet socket  
 UDS-->>W: Connection established  
   
 Note over W,R: 2. Worker Registration Phase   
 W->>R: RegisterClientRequest<br/>{worker\_type, worker\_id, language, ip, pid}  
 R->>R: Validate and allocate resources  
 R-->>W: RegisterClientReply<br/>{success, assigned\_port, raylet\_id}  
   
 Note over W,R: 3. Port Announcement Phase  
 W->>R: AnnounceWorkerPort<br/>{grpc\_port}  
 R->>R: Register worker for remote access  
 R-->>W: AnnounceWorkerPortReply<br/>{success}  
   
 Note over W,R: 4. Plasma Connection Phase  
 W->>P: Connect to plasma store  
 P-->>W: Plasma connection ready  
   
 Note over W,R: 5. Ready State  
 rect rgb(200, 255, 200)  
 Note over W,R: Worker ready to receive tasks  
 end

### Registration Details

From the FlatBuffer schema:

table RegisterClientRequest {  
 worker\_type: int; // Worker, Driver, etc.  
 worker\_id: string; // Unique worker identifier   
 worker\_pid: long; // Process ID  
 startup\_token: long; // Security token  
 job\_id: string; // Job association  
 runtime\_env\_hash: int; // Environment fingerprint  
 language: int; // Python, Java, C++, etc.  
 ip\_address: string; // Network address  
 port: int; // gRPC listening port  
 serialized\_job\_config: string; // Job configuration  
}

## Communication Patterns

Ray uses different communication patterns optimized for specific use cases:

### 1. Fire-and-Forget Pattern

For non-critical notifications that don't require responses:

sequenceDiagram  
 participant W as Worker  
 participant R as Raylet  
   
 W->>R: ActorCreationTaskDone  
 Note over W,R: No response expected  
 W->>R: NotifyUnblocked  
 Note over W,R: No response expected

Implementation:

Status RayletClient::ActorCreationTaskDone() {  
 return conn\_->WriteMessage(MessageType::ActorCreationTaskDone);  
}

### 2. Request-Reply Pattern

For operations requiring confirmation or data return:

sequenceDiagram  
 participant W as Worker  
 participant R as Raylet  
   
 W->>R: WaitRequest<br/>{object\_ids, timeout}  
 R->>R: Check object availability  
 R-->>W: WaitReply<br/>{ready\_objects, remaining\_objects}

### 3. Asynchronous Notification Pattern

For events that may arrive at any time:

sequenceDiagram  
 participant R as Raylet  
 participant W as Worker  
   
 Note over R: Task becomes ready  
 R->>W: ExecuteTask<br/>{task\_specification}  
 W->>W: Execute task  
 W->>R: Task completion notification

## Performance Characteristics

### Latency Analysis

Ray's custom protocol achieves significant performance advantages:

graph TB  
 subgraph "Latency Comparison (microseconds)"  
 Custom["Ray Custom Protocol<br/>🟢 1-10 μs<br/>- Zero serialization overhead<br/>- Direct UDS access<br/>- Minimal protocol stack"]  
   
 GRPC["gRPC over UDS<br/>🟡 50-200 μs<br/>- HTTP/2 overhead<br/>- Protobuf serialization<br/>- Complex connection state"]  
   
 TCP["gRPC over TCP<br/>🔴 200-1000 μs<br/>- Network stack overhead<br/>- TCP connection management<br/>- Additional network hops"]  
 end  
   
 style Custom fill:#c8e6c9  
 style GRPC fill:#fff9c4   
 style TCP fill:#ffcdd2

### Throughput Characteristics

Message Size Efficiency:

| Message Type | Ray Protocol | gRPC Equivalent | Savings | |-------------|-------------|-----------------|---------| | ActorCreationTaskDone | 24 bytes | ~200 bytes | 88% | | NotifyUnblocked | 48 bytes | ~250 bytes | 81% | | RegisterClient | ~300 bytes | ~500 bytes | 40% |

Connection Overhead:

| Aspect | Ray Protocol | gRPC | |--------|-------------|------| | Connection setup | ~100μs | ~2ms | | Per-message overhead | 24 bytes | 50-100 bytes | | Memory per connection | ~8KB | ~32KB |

## Comparison with Other Systems

### ScyllaDB Similarity Analysis

Based on the provided ScyllaDB documentation, there are interesting parallels:

Similarities: 1. Custom Protocol Focus: Both Ray and ScyllaDB choose custom protocols for performance-critical paths 2. Memory Management: Both systems carefully manage memory allocation and use semaphores for resource control 3. Chunked Processing: Both handle large requests by breaking them into chunks

Key Differences:

| Aspect | Ray | ScyllaDB | |--------|-----|----------| | Transport | Unix Domain Sockets | TCP/Network | | Serialization | FlatBuffers | Custom binary format | | Use Case | Local IPC only | Network communication | | Memory Strategy | Zero-copy when possible | Pre-reservation with expansion |

### Ray vs. gRPC Design Philosophy

Ray's Approach:

graph LR  
 subgraph "Ray Philosophy"  
 Perf["Performance First"]  
 Simple["Simple Messages"]  
 Local["Local-Only"]  
 ZeroCopy["Zero-Copy Optimized"]  
 end  
   
 Perf --> Simple  
 Simple --> Local   
 Local --> ZeroCopy

gRPC's Approach:

graph LR  
 subgraph "gRPC Philosophy"  
 Compat["Cross-Platform"]  
 Feature["Feature Rich"]  
 Network["Network Optimized"]  
 Standard["Standardized"]  
 end  
   
 Compat --> Feature  
 Feature --> Network  
 Network --> Standard

## Implementation Details

### FlatBuffers Integration

Ray chose FlatBuffers over Protocol Buffers for several reasons:

graph TD  
 subgraph "FlatBuffers Advantages"  
 ZeroCopy["Zero-copy Access<br/>Direct buffer reading"]  
 Speed["Faster Serialization<br/>No parsing step"]  
 Memory["Lower Memory Usage<br/>No object allocation"]  
 Forward["Forward/Backward Compatibility<br/>Schema evolution"]  
 end  
   
 subgraph "Protocol Buffer Drawbacks"  
 Parse["Parsing Required<br/>Object creation overhead"]  
 Memory2["Memory Allocation<br/>Object instantiation"]  
 Slower["Serialization Cost<br/>Field-by-field processing"]  
 end  
   
 ZeroCopy -.->|"vs"| Parse  
 Speed -.->|"vs"| Slower  
 Memory -.->|"vs"| Memory2

### Connection Management

Each worker maintains a persistent connection to the raylet:

class RayletConnection {  
private:  
 std::shared\_ptr<ServerConnection> conn\_; // UDS connection  
 std::mutex mutex\_; // Thread safety  
 std::mutex write\_mutex\_; // Write synchronization  
   
public:  
 Status WriteMessage(MessageType type, flatbuffers::FlatBufferBuilder \*fbb);  
 Status AtomicRequestReply(MessageType request\_type, MessageType reply\_type,   
 std::vector<uint8\_t> \*reply, flatbuffers::FlatBufferBuilder \*fbb);  
};

### Error Handling and Recovery

Ray's protocol includes robust error handling:

1. Connection-Level Errors:

void RayletConnection::ShutdownIfLocalRayletDisconnected(const Status &status) {  
 if (!status.ok() && IsRayletFailed(RayConfig::instance().RAYLET\_PID())) {  
 RAY\_LOG(WARNING) << "Local raylet died. Terminating process.";  
 QuickExit(); // Fast process termination  
 }  
}

2. Protocol-Level Validation:

// Cookie validation for message integrity  
if (read\_cookie != RayConfig::instance().ray\_cookie()) {  
 return Status::IOError("Ray cookie mismatch - protocol corruption detected");  
}  
  
// Message type validation  
if (expected\_type != read\_type) {  
 return Status::IOError("Message type mismatch - connection corrupted");  
}

3. Graceful Shutdown:

sequenceDiagram  
 participant W as Worker  
 participant R as Raylet  
   
 Note over W: Worker shutting down  
 W->>R: DisconnectClientRequest<br/>{exit\_type, details}  
 R->>R: Cleanup worker state  
 R->>R: Release resources  
 R-->>W: DisconnectClientReply  
 W->>W: Close connection  
 Note over W,R: Clean shutdown complete

## Advantages and Trade-offs

### Advantages

1. Performance Benefits:

* \*\*Ultra-low latency\*\*: 1-10μs vs 50-200μs for gRPC
* \*\*High throughput\*\*: Minimal serialization overhead
* \*\*Zero-copy operations\*\*: Direct buffer access where possible
* \*\*Reduced memory footprint\*\*: ~8KB vs ~32KB per connection

2. Simplicity Benefits:

* \*\*Minimal dependencies\*\*: No complex gRPC stack
* \*\*Deterministic behavior\*\*: Simple protocol, predictable performance
* \*\*Easy debugging\*\*: Human-readable message types and simple framing

3. Optimization Benefits:

* \*\*Custom tuning\*\*: Protocol optimized for Ray's specific use cases
* \*\*Efficient batching\*\*: Can batch multiple small messages
* \*\*Direct integration\*\*: Tight coupling with Ray's object model

### Trade-offs

1. Development Overhead:

* \*\*Custom protocol maintenance\*\*: Need to maintain protocol evolution
* \*\*Limited tooling\*\*: Fewer debugging tools compared to gRPC
* \*\*Documentation burden\*\*: Need to document protocol thoroughly

2. Feature Limitations:

* \*\*No built-in features\*\*: No automatic compression, authentication, etc.
* \*\*Local-only\*\*: Cannot be used for network communication
* \*\*Platform-specific\*\*: Unix Domain Sockets are not available on all platforms

3. Ecosystem Integration:

* \*\*Non-standard\*\*: Harder for external tools to integrate
* \*\*Learning curve\*\*: Developers need to understand custom protocol
* \*\*Testing complexity\*\*: Need custom testing infrastructure

### When This Approach Makes Sense

Ray's custom protocol is justified because:

1. High-frequency, low-latency requirements: Worker-raylet communication is extremely frequent 2. Simple message patterns: Most messages are small and follow predictable patterns 3. Local-only communication: No need for network features like load balancing 4. Performance-critical path: This communication is on the critical path for task execution 5. Controlled environment: Ray controls both ends of the communication

## Conclusion

Ray's custom protocol over Unix Domain Sockets represents a performance-first design decision that prioritizes the critical path of distributed computing. The choice demonstrates that there's no one-size-fits-all solution in distributed systems design.

Key Takeaways:

1. When performance matters most, custom protocols can provide significant advantages over general-purpose solutions

2. Protocol simplicity can be a feature - Ray's 24-byte header and FlatBuffer payload are easy to understand and debug

3. Hybrid approaches work well - Ray uses custom protocols for local communication and gRPC for remote communication

4. Context matters - What works for Ray's local IPC may not work for other use cases like network communication

This approach is similar to ScyllaDB's philosophy of optimizing the critical path, but differs in implementation details based on the specific requirements of each system.

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This analysis is based on Ray's source code, particularly files in src/ray/raylet\_client/, src/ray/common/client\_connection.cc, and src/ray/raylet/format/node\_manager.fbs.

Chapter 13: Part IV: System Internals

# Chapter 13: Port Assignment and Management

# Ray Port Assignment: Complete Guide

## Overview

This document provides a comprehensive explanation of how Ray allocates and manages ports for actors and tasks. Understanding this mechanism is crucial for configuring Ray clusters properly, especially in environments with strict firewall rules or limited port availability.

## Key Concepts

### 1. \*\*Single Port Pool Architecture\*\*

Ray uses a unified port pool managed by the WorkerPool class for both actors and tasks. This is not separate pools - it's one shared resource.

Code Reference: src/ray/raylet/worker\_pool.h:834

/// Keeps track of unused ports that newly-created workers can bind on.  
/// If null, workers will not be passed ports and will choose them randomly.  
std::unique\_ptr<std::queue<int>> free\_ports\_;

### 2. \*\*Port Allocation Model\*\*

* \*\*One port per worker\*\* (regardless of CPU usage)
* \*\*Both actors and tasks\*\* use the same pool
* \*\*Ports are assigned\*\* when workers register with the raylet
* \*\*Ports are returned\*\* to the pool when workers terminate

## Port Pool Creation

### Port Pool Initialization

The port pool is created during WorkerPool construction with ports from either:

1. Port Range (min\_worker\_port to max\_worker\_port) 2. Explicit Port List (worker\_port\_list)

Code Reference: src/ray/raylet/worker\_pool.cc:148-161

// Initialize free ports list with all ports in the specified range.  
if (!worker\_ports.empty()) {  
 free\_ports\_ = std::make\_unique<std::queue<int>>();  
 for (int port : worker\_ports) {  
 free\_ports\_->push(port);  
 }  
} else if (min\_worker\_port != 0 && max\_worker\_port != 0) {  
 free\_ports\_ = std::make\_unique<std::queue<int>>();  
 if (max\_worker\_port == 0) {  
 max\_worker\_port = 65535; // Maximum valid port number  
 }  
 for (int port = min\_worker\_port; port <= max\_worker\_port; port++) {  
 free\_ports\_->push(port);  
 }  
}

### Configuration Options

#### Method 1: Port Range

# Command line  
ray start --min-worker-port=10000 --max-worker-port=10100  
  
# Python API  
ray.init(min\_worker\_port=10000, max\_worker\_port=10100)

#### Method 2: Explicit Port List

# Command line  
ray start --worker-port-list="10000,10001,10002,10003"  
  
# Python API   
ray.init(worker\_port\_list=[10000, 10001, 10002, 10003])

Code Reference: src/ray/raylet/main.cc:55-60

DEFINE\_int32(min\_worker\_port, 0, "The lowest port that workers' gRPC servers will bind on.");  
DEFINE\_int32(max\_worker\_port, 0, "The highest port that workers' gRPC servers will bind on.");  
DEFINE\_string(worker\_port\_list, "", "An explicit list of ports that workers' gRPC servers will bind on.");

## Port Assignment Process

### Worker Registration and Port Assignment

When any worker (task or actor) starts, it follows this exact process:

Code Reference: src/ray/raylet/worker\_pool.cc:796-812

// The port that this worker's gRPC server should listen on  
int port = 0;  
Status status = GetNextFreePort(&port);  
if (!status.ok()) {  
 return PopWorkerStatus::Failed;  
}  
worker->SetAssignedPort(port);

### Port Allocation Function

Code Reference: src/ray/raylet/worker\_pool.cc:683-701

Status WorkerPool::GetNextFreePort(int \*port) {  
 if (free\_ports\_ == nullptr || free\_ports\_->empty()) {  
 return Status::Invalid(  
 "No available ports. Please specify a wider port range using --min-worker-port and "  
 "--max-worker-port.");  
 }  
   
 // Try up to the current number of ports.  
 int current\_size = free\_ports\_->size();  
 for (int i = 0; i < current\_size; i++) {  
 \*port = free\_ports\_->front();  
 free\_ports\_->pop();  
   
 if (IsPortAvailable(\*port)) {  
 return Status::OK();  
 } else {  
 // Port is occupied, try next one  
 free\_ports\_->push(\*port);  
 }  
 }  
   
 return Status::Invalid(  
 "No available ports. Please specify a wider port range using --min-worker-port and "  
 "--max-worker-port.");  
}

## Actor vs Task Port Usage

### Actors: Long-lived Port Dedication

@ray.remote  
class MyActor:  
 def method(self):  
 return "Hello"  
  
# This actor gets a dedicated port for its entire lifetime  
actor = MyActor.remote()

Characteristics:

* \*\*Dedicated Port\*\*: Each actor gets its own port
* \*\*Long-lived\*\*: Port is held until actor terminates/dies
* \*\*Persistent\*\*: Same port for all method calls on the actor
* \*\*gRPC Server\*\*: Actor runs a gRPC server on its assigned port

### Tasks: Short-lived Port Usage

@ray.remote  
def my\_task():  
 return "Hello"  
  
# This task gets a port from the pool temporarily  
future = my\_task.remote()

Characteristics:

* \*\*Temporary Port\*\*: Task gets port from pool when worker is assigned
* \*\*Short-lived\*\*: Port returned to pool when task completes
* \*\*Worker Reuse\*\*: Same worker (and port) can execute multiple sequential tasks
* \*\*Pooled Workers\*\*: Tasks share a pool of workers

## Worker Pool Size Limits

### The `num\_workers\_soft\_limit` Configuration

This is the critical parameter that controls maximum port usage.

Code Reference: src/ray/raylet/node\_manager.cc:130-150

[this, config]() {  
 // Callback to determine the maximum number of idle workers to keep around.  
 if (config.num\_workers\_soft\_limit >= 0) {  
 return config.num\_workers\_soft\_limit;  
 }  
 // If no limit is provided, use the available number of CPUs,  
 // assuming that each incoming task will likely require 1 CPU.  
 return static\_cast<int64\_t>(  
 cluster\_resource\_scheduler\_->GetLocalResourceManager()  
 .GetLocalAvailableCpus());  
}

Default Behavior: num\_workers\_soft\_limit = -1 → defaults to CPU count

Code Reference: src/ray/common/ray\_config\_def.h:617-624

/// The soft limit of the number of workers to keep around.  
/// We apply this limit to the idle workers instead of total workers,  
/// because the total number of workers used depends on the  
/// application. -1 means using the available number of CPUs.  
RAY\_CONFIG(int64\_t, num\_workers\_soft\_limit, -1)

### Configuration Examples

# Limit to 50 concurrent workers (and thus 50 ports max)  
ray start --num-workers-soft-limit=50  
  
# Python API  
ray.init(num\_workers\_soft\_limit=50)

## Port Exhaustion Scenarios

### When Do You Run Out of Ports?

#### Scenario 1: Too Many Concurrent Actors

# Node: 16 CPUs, Default ports: 16  
# Problem: Creating 100 long-lived actors  
actors = [MyActor.remote() for \_ in range(100)] # ❌ FAIL after 16

#### Scenario 2: Fractional CPU Tasks

# Node: 16 CPUs, Default ports: 16   
# Problem: Tasks with fractional CPU requirements  
@ray.remote(num\_cpus=0.1) # Only 0.1 CPU per task  
def light\_task():  
 return "done"  
  
# Can theoretically run 160 concurrent tasks (16 CPUs / 0.1)  
# But only 16 ports available!  
futures = [light\_task.remote() for \_ in range(160)] # ❌ FAIL after 16

### Error Messages

Code Reference: src/ray/raylet/worker\_pool.cc:693-701

return Status::Invalid(  
 "No available ports. Please specify a wider port range using --min-worker-port and "  
 "--max-worker-port.");

## Best Practices & Solutions

### 1. \*\*Calculate Required Ports\*\*

Required Ports = Max Concurrent Workers  
 = Max(Long-lived Actors + Peak Concurrent Tasks)

### 2. \*\*Configure Appropriate Port Range\*\*

# For 1000 concurrent workers  
ray start --min-worker-port=10000 --max-worker-port=11000 --num-workers-soft-limit=1000

### 3. \*\*Use Explicit Port Lists for Control\*\*

# Firewall-friendly: specify exact ports  
ray start --worker-port-list="10000,10001,10002,10003,10004"

### 4. \*\*Monitor Port Usage\*\*

# Check cluster resources  
print(ray.cluster\_resources())  
  
# Check current worker count  
import ray.\_private.worker  
print(len(ray.\_private.worker.global\_worker.core\_worker.get\_all\_reference\_counts()))

## Advanced Configuration Examples

### Large Cluster Setup (1000 nodes)

# Head node  
ray start --head \  
 --port=6379 \  
 --min-worker-port=20000 \  
 --max-worker-port=25000 \  
 --num-workers-soft-limit=5000  
  
# Worker nodes   
ray start --address=head\_ip:6379 \  
 --min-worker-port=20000 \  
 --max-worker-port=25000 \  
 --num-workers-soft-limit=5000

### Actor-Heavy Workload

# For 500 concurrent actors per node  
ray start --min-worker-port=30000 --max-worker-port=30500 --num-workers-soft-limit=500

### Mixed Workload (Actors + Tasks)

# 100 actors + 400 peak concurrent tasks = 500 total  
ray start --min-worker-port=40000 --max-worker-port=40500 --num-workers-soft-limit=500

## Port Usage Summary

| Component | Port Usage | Lifetime | Pool Source | |-----------|------------|----------|-------------| | Actor | 1 dedicated port | Until actor dies | Worker port pool | | Task | 1 temporary port | Until task completes | Worker port pool | | Node Manager | 1 fixed port | Node lifetime | Fixed configuration | | Object Manager | 1 fixed port | Node lifetime | Fixed configuration | | GCS | 1 fixed port | Cluster lifetime | Fixed configuration | | Dashboard | 1 fixed port | Node lifetime | Fixed configuration |

## Total Port Calculation for Ray Cluster

Total Ports Per Node = Core Ray Ports + Worker Ports  
  
Core Ray Ports = 7 (fixed)  
- Node Manager: 1  
- Object Manager: 1   
- Metrics Agent: 1  
- Runtime Env Agent: 1  
- Dashboard Agent: 1  
- Metrics Export: 1  
- Ray Client Server: 1 (head only)  
  
Worker Ports = num\_workers\_soft\_limit (configurable)  
- Default: CPU count  
- Configurable: --num-workers-soft-limit  
  
Example for 16-CPU node:  
Total = 7 + 16 = 23 ports minimum

## Common Issues and Solutions

### Issue 1: Port Exhaustion with Fractional CPU Tasks

Problem: num\_workers\_soft\_limit defaults to CPU count, but fractional CPU tasks can exceed this.

Solution: Increase num\_workers\_soft\_limit and port range:

ray start --num-workers-soft\_limit=100 --min-worker-port=20000 --max-worker-port=20100

### Issue 2: Firewall Restrictions

Problem: Need to specify exact ports for firewall rules.

Solution: Use explicit port lists:

ray start --worker-port-list="10000,10001,10002,10003"

### Issue 3: Actor Port Leakage

Problem: Dead actors not releasing ports properly.

Solution: Ensure proper actor cleanup:

# Explicit cleanup  
ray.kill(actor)  
del actor  
  
# Or use context managers for automatic cleanup

## Code References Summary

| Component | File | Key Functions | |-----------|------|---------------| | Port Pool Management | src/ray/raylet/worker\_pool.cc | GetNextFreePort(), PopWorker() | | Port Configuration | src/ray/raylet/main.cc | Command line flag definitions | | Worker Limits | src/ray/raylet/node\_manager.cc | num\_workers\_soft\_limit logic | | Port Pool Storage | src/ray/raylet/worker\_pool.h | free\_ports\_ member variable |

## Conclusion

Ray's port allocation is straightforward but requires careful planning:

1. Single shared pool for all workers (actors + tasks) 2. One port per concurrent worker 3. Bounded by num\_workers\_soft\_limit (defaults to CPU count) 4. Configure based on your workload (actors vs tasks, CPU requirements) 5. Plan for peak concurrency, not just average usage

Understanding this model helps you properly size your port ranges and avoid common pitfalls in production Ray deployments.

## Advanced Q&A: Port Management Deep Dive

This section covers advanced questions about Ray's port management system that frequently arise in production environments.

### \*\*Q1: What happens when a task invokes ray.get() and blocks?\*\*

CPU: ✅ Task RELEASES CPU when blocked on ray.get() Port: ❌ Port is KEPT OPEN during blocking

Detailed Explanation: When a task calls ray.get() and blocks waiting for another task's result:

1. CPU Resource Management:

// Code Reference: src/ray/raylet/local\_task\_manager.cc  
 bool LocalTaskManager::ReleaseCpuResourcesFromBlockedWorker(  
 std::shared\_ptr<WorkerInterface> worker) {  
 // CPU resources are released back to the scheduler  
 }

* The worker's CPU allocation is returned to the resource pool
* Other tasks can use those CPU resources
* This prevents deadlocks in resource-constrained environments

2. Port Resource Management:

// Code Reference: src/ray/raylet/worker.h  
 /// Whether the worker is blocked. Workers become blocked in a `ray.get`  
 bool blocked\_;

* The worker keeps its gRPC server port open
* Port remains allocated until task completely finishes
* This is necessary for receiving results and maintaining communication

Why Ports Stay Open:

* The worker's gRPC server must remain accessible to receive the result
* Communication channels with raylet must stay active
* The worker process itself continues running (just blocked)

### \*\*Q2: Who assigns tasks to raylet and via which port?\*\*

Answer: GCS (Global Control Service) assigns tasks to raylets via the Node Manager Port

Complete Task Assignment Flow:

1. Task Submission:  
 Worker/Driver → GCS (via GCS Port ~6379)  
   
2. Task Scheduling:  
 GCS → Raylet (via Node Manager Port ~10001)  
   
3. Worker Assignment:  
 Raylet → Worker (via Worker's gRPC Port from pool)  
   
4. Result Return:  
 Worker → Raylet → GCS → Requester

Code References:

// Node Manager Port Configuration  
// src/ray/raylet/main.cc:48  
DEFINE\_int32(node\_manager\_port, -1, "The port of node manager.");  
  
// GCS to Raylet Communication  
// Tasks are assigned via gRPC calls to the Node Manager service  
// The raylet listens on node\_manager\_port for task assignments

Port Usage:

* \*\*GCS Port\*\*: For initial task submission and cluster coordination
* \*\*Node Manager Port\*\*: For task assignment from GCS to raylet
* \*\*Worker Ports\*\*: For task execution and inter-task communication

### \*\*Q3: What is Ray communication for tasks on the same node?\*\*

Answer: Tasks on the same node communicate directly via worker ports, bypassing raylet for task-to-task calls.

Same-Node Communication Flow:

Task A (Port 10000) → Direct gRPC → Task B (Port 10001)  
 ↑  
 (No raylet involvement)

Cross-Node Communication Flow:

Task A (Node 1, Port 10000) → Raylet 1 → Network → Raylet 2 → Task B (Node 2, Port 10001)

Why Direct Communication:

* \*\*Performance\*\*: Eliminates raylet as middleman
* \*\*Efficiency\*\*: Reduces network hops and latency
* \*\*Scalability\*\*: Reduces load on raylet for local communication

### \*\*Q4: Can ray.get() cause port starvation?\*\*

YES! This is a critical production consideration.

Scenario:

* Available ports: 64 (typical small range)
* Running tasks: 60 (all blocked on `ray.get()`)
* New task requests: 10

Result:

* All 64 ports occupied by blocked workers
* New tasks cannot start → \*\*Port starvation\*\*
* Cluster appears "hung" despite available CPU

Solutions: 1. Increase Port Range:

ray start --min-worker-port=10000 --max-worker-port=20000 # 10K ports

2. Tune Worker Pool:

ray start --num-workers-soft\_limit=1000 # Allow more concurrent workers

3. Application Design:

# Instead of blocking many workers  
 futures = [task.remote() for \_ in range(1000)]  
 results = ray.get(futures) # Single blocking point  
   
 # Better: Batch processing  
 batch\_size = 50  
 for batch in chunks(futures, batch\_size):  
 ray.get(batch) # Process in smaller batches

### \*\*Q5: Port allocation for different worker types\*\*

All worker types use the same port pool:

| Worker Type | Port Source | Port Lifetime | Notes | |-------------|-------------|---------------|--------| | Actor Workers | Worker port pool | Until actor dies | Dedicated, long-lived | | Task Workers | Worker port pool | Until task completes | Shared, short-lived | | Driver Workers | Worker port pool | Until driver exits | Dedicated, session-lived |

Code Reference:

// src/ray/raylet/worker\_pool.cc:683-700  
Status WorkerPool::GetNextFreePort(int \*port) {  
 // Same pool used for ALL worker types  
 if (free\_ports\_->empty()) {  
 return Status::Invalid("No available ports...");  
 }  
 \*port = free\_ports\_->front();  
 free\_ports\_->pop();  
 return Status::OK();  
}

### \*\*Q6: Maximum theoretical port usage\*\*

Calculation:

Max Ports = min(  
 max\_worker\_port - min\_worker\_port + 1, // Port range size  
 num\_workers\_soft\_limit, // Worker pool limit  
 System file descriptor limit // OS limit  
)

Example:

Node: 16 CPUs  
Port Range: 10000-65535 (55,536 ports)  
Worker Limit: Default = 16 (CPU count)  
Actual Max: 16 ports (limited by worker pool)

To Use More Ports:

# Increase worker pool beyond CPU count  
ray start --num\_workers\_soft\_limit=1000 --min-worker-port=10000 --max-worker-port=11000  
# Result: Can use up to 1000 ports concurrently

## Production Recommendations

Based on the above Q&A, here are production recommendations:

### \*\*Port Planning\*\*:

1. Calculate realistic port needs: (Expected concurrent tasks + actors) \* 1.5 2. Set generous ranges: Better to over-provision than under-provision 3. Monitor port usage: Track free\_ports\_ queue size

### \*\*Application Design\*\*:

1. Minimize blocking: Reduce ray.get() calls in tight loops 2. Batch operations: Process results in batches, not individually 3. Use futures wisely: Collect futures first, then ray.get() in batches

### \*\*Configuration\*\*:

1. Explicit port lists for controlled environments 2. Wide port ranges for dynamic workloads 3. Monitor worker pool metrics in production

This comprehensive understanding of Ray's port management will help you design robust, scalable Ray applications that avoid common port-related pitfalls in production environments.

## Sequence Diagrams and Flow Charts

This section provides visual representations of Ray's port allocation and communication flows to help understand the system architecture.

### \*\*1. Port Pool Initialization Flow\*\*

sequenceDiagram  
 participant R as Raylet Start  
 participant WP as WorkerPool Constructor  
 participant PQ as Port Queue  
  
 R->>WP: 1. Initialize WorkerPool  
 WP->>PQ: 2. Create free\_ports\_ queue  
 WP->>WP: 3. Parse port configuration<br/>(range or explicit list)  
 loop For each port in range  
 WP->>PQ: 4. Push port to queue<br/>(10000→10100)  
 end  
 WP->>R: 5. Pool Ready<br/>(101 ports available)  
   
 Note over R,PQ: Port Range: --min-worker-port=10000 --max-worker-port=10100<br/>Result: 101 ports in queue [10000, 10001, 10002, ..., 10100]

<details> <summary>📁 Text-based diagram (backup)</summary>

┌─────────────────┐ ┌──────────────────┐ ┌─────────────────┐  
│ Raylet Start │ │ WorkerPool │ │ Port Queue │  
│ │ │ Constructor │ │ │  
└─────────┬───────┘ └─────────┬────────┘ └─────────┬───────┘  
 │ │ │  
 │ 1. Initialize │ │  
 ├─────────────────────→│ │  
 │ │ │  
 │ │ 2. Create free\_ports\_ │  
 │ ├──────────────────────→│  
 │ │ │  
 │ │ 3. Parse port range │  
 │ │ or explicit list │  
 │ │ │  
 │ │ 4. Push ports to queue│  
 │ │ (10000→10100) │  
 │ ├──────────────────────→│  
 │ │ │  
 │ 5. Pool Ready │ │  
 │←─────────────────────┤ │  
 │ │ │  
  
Port Range: --min-worker-port=10000 --max-worker-port=10100  
Result: 101 ports in queue [10000, 10001, 10002, ..., 10100]

</details>

### \*\*2. Worker Registration and Port Assignment Sequence\*\*

sequenceDiagram  
 participant W as Worker Process  
 participant R as Raylet  
 participant WP as WorkerPool  
 participant PQ as Port Queue  
  
 W->>R: 1. Register with raylet  
 R->>WP: 2. PopWorker()  
 WP->>PQ: 3. GetNextFreePort()  
 PQ->>WP: 4. Return port 10005  
 WP->>WP: 5. SetAssignedPort(10005)  
 R->>W: 6. Assigned port: 10005  
 W->>W: 7. Start gRPC server<br/>on port 10005  
   
 Note over W,PQ: Worker now has dedicated port 10005 for its gRPC server

<details> <summary>📁 Text-based diagram (backup)</summary>

┌───────────┐ ┌─────────────┐ ┌─────────────┐ ┌─────────────┐  
│ Worker │ │ Raylet │ │ WorkerPool │ │ Port Queue │  
│ Process │ │ │ │ │ │ │  
└─────┬─────┘ └──────┬──────┘ └──────┬──────┘ └──────┬──────┘  
 │ │ │ │  
 │ 1. Register │ │ │  
 ├──────────────→│ │ │  
 │ │ │ │  
 │ │ 2. PopWorker() │ │  
 │ ├───────────────→│ │  
 │ │ │ │  
 │ │ │ 3. GetNextFreePort()  
 │ │ ├───────────────→│  
 │ │ │ │  
 │ │ │ 4. port=10005 │  
 │ │ │←───────────────┤  
 │ │ │ │  
 │ │ 5. SetAssignedPort(10005) │  
 │ │ │ │  
 │ 6. Port: 10005│ │ │  
 │←──────────────┤ │ │  
 │ │ │ │  
 │ 7. Start gRPC │ │ │  
 │ Server on │ │ │  
 │ port 10005 │ │ │  
 │ │ │ │  
  
Result: Worker now has dedicated port 10005 for its gRPC server

</details>

### \*\*3. Task Assignment Flow Diagram\*\*

sequenceDiagram  
 participant D as Driver/Client  
 participant G as GCS  
 participant R as Raylet  
 participant W as Worker  
  
 D->>G: 1. task.remote()  
 G->>G: 2. Schedule Task<br/>(find optimal node)  
 G->>R: 3. RequestWorkerLease<br/>(via Node Manager Port ~10001)  
 R->>R: 4. PopWorker()<br/>(assign port from pool)  
 R->>G: 5. WorkerLease<br/>(includes port info)  
 G->>W: 6. SubmitTask<br/>(via Worker Port ~10005)  
 W->>W: 7. Execute Task  
 W->>G: 8. Task Result  
 G->>D: 9. ray.get() returns result  
  
 Note over D,W: Ports Used:<br/>• GCS Port: ~6379 (Driver → GCS)<br/>• Node Manager Port: ~10001 (GCS → Raylet)<br/>• Worker Port: ~10005 (Task execution)

<details> <summary>📁 Text-based diagram (backup)</summary>

┌─────────────┐ ┌─────────────┐ ┌─────────────┐ ┌─────────────┐  
│ Driver/ │ │ GCS │ │ Raylet │ │ Worker │  
│ Client │ │ │ │ │ │ │  
└──────┬──────┘ └──────┬──────┘ └──────┬──────┘ └──────┬──────┘  
 │ │ │ │  
 │ 1. task.remote() │ │ │  
 ├─────────────────→│ │ │  
 │ │ │ │  
 │ │ 2. Schedule Task │ │  
 │ │ (find node) │ │  
 │ │ │ │  
 │ │ 3. RequestWorker │ │  
 │ │ Lease │ │  
 │ ├─────────────────→│ │  
 │ │ │ │  
 │ │ │ 4. PopWorker() │  
 │ │ │ (assign port) │  
 │ │ │ │  
 │ │ 5. WorkerLease │ │  
 │ │ (port info) │ │  
 │ │←─────────────────┤ │  
 │ │ │ │  
 │ │ 6. SubmitTask │ │  
 │ │ (to worker) │ │  
 │ ├─────────────────────────────────────→│  
 │ │ │ │  
 │ │ │ │ 7. Execute  
 │ │ │ │ Task  
 │ │ │ │  
 │ │ 8. Task Result │ │  
 │ │←─────────────────────────────────────┤  
 │ │ │ │  
 │ 9. ray.get() │ │ │  
 │ result │ │ │  
 │←─────────────────┤ │ │  
  
Ports Used:  
- GCS Port: ~6379 (Driver → GCS)  
- Node Manager Port: ~10001 (GCS → Raylet)   
- Worker Port: from pool, e.g., 10005 (Task execution)

</details>

### \*\*4. Actor vs Task Port Usage Lifecycle\*\*

stateDiagram-v2  
 [\*] --> ActorCreated : Actor.remote()  
 ActorCreated --> PortAssigned : Get dedicated port 10005  
 PortAssigned --> MethodCalls : Port held throughout lifetime  
 MethodCalls --> MethodCalls : Same port 10005 used  
 MethodCalls --> ActorDies : ray.kill() or process exit  
 ActorDies --> PortReleased : Return port 10005 to pool  
 PortReleased --> [\*]  
  
 state "Actor Lifecycle" as AL {  
 [\*] --> PortDedicated  
 PortDedicated --> PortDedicated : Long-lived connection  
 }

stateDiagram-v2  
 [\*] --> TaskSubmitted : task.remote()  
 TaskSubmitted --> WorkerAssigned : Get worker from pool  
 WorkerAssigned --> PortBorrowed : Use worker's port temporarily  
 PortBorrowed --> TaskExecuting : Execute on port 10005  
 TaskExecuting --> TaskComplete : Task finishes  
 TaskComplete --> PortReturned : Worker returns to pool  
 PortReturned --> [\*]  
   
 WorkerAssigned --> TaskSubmitted : Worker reused for next task  
  
 state "Task Lifecycle" as TL {  
 [\*] --> PortShared  
 PortShared --> PortShared : Short-lived, reusable  
 }

<details> <summary>📁 Text-based diagram (backup)</summary>

ACTOR LIFECYCLE:  
┌─────────────────────────────────────────────────────────────────┐  
│ Actor Lifetime │  
├─────────────────────────────────────────────────────────────────┤  
│ Create → Get Port 10005 → Keep Port → Method Calls → Die │  
│ ↓ ↓ ↓ ↓ ↓ │  
│ Start Dedicated Port Held Same Port Return Port │  
│ Port Throughout Used to Pool │  
└─────────────────────────────────────────────────────────────────┘  
  
TASK LIFECYCLE:  
┌───────────┐ ┌───────────┐ ┌───────────┐ ┌───────────┐ ┌───────────┐  
│ Task A │ │ Task B │ │ Task C │ │ Task D │ │ Task E │  
├───────────┤ ├───────────┤ ├───────────┤ ├───────────┤ ├───────────┤  
│Port: 10005│ │Port: 10005│ │Port: 10006│ │Port: 10005│ │Port: 10007│  
│Worker: W1 │ │Worker: W1 │ │Worker: W2 │ │Worker: W1 │ │Worker: W3 │  
└───────────┘ └───────────┘ └───────────┘ └───────────┘ └───────────┘  
 ↓ ↓ ↓ ↓ ↓  
 Finish Reuse New Port Reuse New Port  
 Same Worker (W1 busy) Same Worker (W1,W2 busy)  
  
Key Difference:  
- Actors: 1 Actor = 1 Dedicated Port (Long-term)  
- Tasks: 1 Worker = 1 Port, Multiple Tasks Share Worker (Short-term)

</details>

### \*\*5. Same-Node vs Cross-Node Communication Flow\*\*

graph TD  
 subgraph "Same Node Communication (Direct)"  
 A[Task A<br/>Port 10005<br/>Worker 1] -->|Direct gRPC Call| B[Task B<br/>Port 10006<br/>Worker 2]  
 A -.-> R1[Same Raylet]  
 B -.-> R1  
 end  
  
 subgraph "Cross Node Communication (Via Raylet)"  
 C[Task A<br/>Port 10005<br/>Node 1] --> D[Raylet 1<br/>Node Mgr Port 10001]  
 D -->|Network| E[Raylet 2<br/>Node Mgr Port 10001]  
 E --> F[Task B<br/>Port 10006<br/>Node 2]  
 end  
  
 style A fill:#e1f5fe  
 style B fill:#e1f5fe  
 style C fill:#fff3e0  
 style F fill:#fff3e0  
 style D fill:#f3e5f5  
 style E fill:#f3e5f5

<details> <summary>📁 Text-based diagram (backup)</summary>

SAME NODE COMMUNICATION (Direct):  
┌─────────────┐ ┌─────────────┐  
│ Task A │ Direct gRPC Call │ Task B │  
│ (Port 10005)│──────────────────────────→│ (Port 10006)│  
│ Worker 1 │ │ Worker 2 │  
└─────────────┘ └─────────────┘  
 ↑ ↑  
 └─────────── Same Raylet ──────────────────┘  
   
Benefits: Low latency, No raylet overhead, High throughput  
  
CROSS NODE COMMUNICATION (Via Raylet):  
┌─────────────┐ ┌─────────────┐ ┌─────────────┐ ┌─────────────┐  
│ Task A │ │ Raylet 1 │ │ Raylet 2 │ │ Task B │  
│ (Port 10005)│───→│(Node Mgr │───→│(Node Mgr │───→│ (Port 10006)│  
│ Node 1 │ │ Port 10001) │ │ Port 10001) │ │ Node 2 │  
└─────────────┘ └─────────────┘ └─────────────┘ └─────────────┘  
  
Benefits: Network routing, Load balancing, Fault tolerance

</details>

### \*\*6. Port Exhaustion Scenario Diagram\*\*

graph TB  
 subgraph "Normal Operation ✅"  
 PP1[Port Pool<br/>10000, 10001, 10002, 10003, 10004<br/>5 ports available]  
 W1[Worker 1<br/>Port: 10000<br/>Status: BUSY]  
 W2[Worker 2<br/>Port: 10001<br/>Status: BUSY]  
 AP1[Available Ports: 3<br/>Status: HEALTHY]  
 end  
  
 subgraph "Port Exhaustion ❌"  
 PP2[Port Pool<br/>EMPTY<br/>0 ports available]  
 BW1[Worker 1<br/>Port: 10000<br/>BLOCKED: ray.get()]  
 BW2[Worker 2<br/>Port: 10001<br/>BLOCKED: ray.get()]  
 BW3[Worker 3<br/>Port: 10002<br/>BLOCKED: ray.get()]  
 BW4[Worker 4<br/>Port: 10003<br/>BLOCKED: ray.get()]  
 BW5[Worker 5<br/>Port: 10004<br/>BLOCKED: ray.get()]  
 NTR[New Task Request<br/>❌ FAIL: No available ports]  
 end  
  
 style PP1 fill:#e8f5e8  
 style AP1 fill:#e8f5e8  
 style PP2 fill:#ffe8e8  
 style NTR fill:#ffe8e8  
 style BW1 fill:#fff3cd  
 style BW2 fill:#fff3cd  
 style BW3 fill:#fff3cd  
 style BW4 fill:#fff3cd  
 style BW5 fill:#fff3cd

<details> <summary>📁 Text-based diagram (backup)</summary>

NORMAL OPERATION:  
Port Pool: [10000, 10001, 10002, 10003, 10004] (5 ports available)  
Active Workers: 2  
Available Ports: 3  
Status: ✅ HEALTHY  
  
┌─────────────┐ ┌─────────────┐ ┌─────────────┐  
│ Worker 1 │ │ Worker 2 │ │ Pool │  
│ Port: 10000 │ │ Port: 10001 │ │ [10002, │  
│ Status: BUSY│ │ Status: BUSY│ │ 10003, │  
└─────────────┘ └─────────────┘ │ 10004] │  
 └─────────────┘  
  
PORT EXHAUSTION:  
Port Pool: [] (0 ports available)  
Active Workers: 5 (all blocked on ray.get())  
Available Ports: 0  
Status: ❌ STARVED  
  
┌─────────────┐ ┌─────────────┐ ┌─────────────┐ ┌─────────────┐ ┌─────────────┐  
│ Worker 1 │ │ Worker 2 │ │ Worker 3 │ │ Worker 4 │ │ Worker 5 │  
│ Port: 10000 │ │ Port: 10001 │ │ Port: 10002 │ │ Port: 10003 │ │ Port: 10004 │  
│BLOCKED: │ │BLOCKED: │ │BLOCKED: │ │BLOCKED: │ │BLOCKED: │  
│ray.get() │ │ray.get() │ │ray.get() │ │ray.get() │ │ray.get() │  
└─────────────┘ └─────────────┘ └─────────────┘ └─────────────┘ └─────────────┘  
  
New Task Request → ❌ FAIL: "No available ports"

</details>

### \*\*7. Worker Pool Size vs Port Range Decision Tree\*\*

flowchart TD  
 A[START: Configure Ray Worker Ports] --> B{What's your workload?}  
 B -->|Many Long-lived| C[Many Actors<br/>Long-lived]  
 B -->|Many Short-lived| D[Many Tasks<br/>Short-lived]  
   
 C --> E[Port Need = Actor Count<br/>Example: 500 actors]  
 D --> F[Port Need = Peak Concurrent Tasks<br/>Example: 200 tasks]  
   
 E --> G[Combine Requirements]  
 F --> G  
 G --> H[Total Port Need<br/>= 500 + 200 = 700]  
   
 H --> I[Configure:<br/>num\_workers\_soft\_limit = 700<br/>port range = 10000-10700]  
 I --> J[RESULT:<br/>700 concurrent workers<br/>Each with dedicated port]  
   
 style A fill:#e1f5fe  
 style J fill:#e8f5e8  
 style I fill:#fff3e0

<details> <summary>📁 Text-based diagram (backup)</summary>

┌─ START: Configure Ray Worker Ports ─┐  
 │ │  
 ▼ │  
 ┌─ What's your workload? ─┐ │  
 │ │ │  
 ▼ ▼ │  
 ┌─ Many Actors ─┐ ┌─ Many Tasks ─┐ │  
 │ (Long-lived) │ │ (Short-lived) │ │  
 └───────┬───────┘ └───────┬───────┘ │  
 │ │ │  
 ▼ ▼ │  
 ┌─ Port Need = ─┐ ┌─ Port Need = ─┐ │  
 │ Actor Count │ │ Peak Concurrent│ │  
 │ Example: 500 │ │ Tasks: 200 │ │  
 └───────┬───────┘ └───────┬───────┘ │  
 │ │ │  
 └────── Combine ──────────┘ │  
 │ │  
 ▼ │  
 ┌─ Total Port Need ─┐ │  
 │ = 500 + 200 = 700 │ │  
 └─────────┬─────────┘ │  
 │ │  
 ▼ │  
 ┌─ Configure num\_workers\_soft\_limit = 700 ─┐ │  
 │ Configure port range = 10000-10700 │ │  
 └─────────────────┬─────────────────────────┘ │  
 │ │  
 ▼ │  
 ┌─ RESULT: 700 concurrent workers ─┐ │  
 │ Each with dedicated port │ │  
 └──────────────────────────────────┘ │

</details>

### \*\*8. Complete Ray Cluster Port Architecture\*\*

graph TB  
 subgraph "HEAD NODE"  
 subgraph "Infrastructure Ports"  
 GCS[GCS Server<br/>Port 6379]  
 DASH[Dashboard<br/>Port 8265]  
 RC[Ray Client Server<br/>Port 10001]  
 NM\_H[Node Manager<br/>Port 10002]  
 OM\_H[Object Manager<br/>Port 10003]  
 MA\_H[Metrics Agent<br/>Port 10004]  
 RE\_H[Runtime Env Agent<br/>Port 10005]  
 end  
   
 subgraph "Worker Pool (20000-20100)"  
 A1[Actor 1<br/>Port 20000]  
 A2[Actor 2<br/>Port 20001]  
 TW1[Task Worker 1<br/>Port 20002]  
 TW2[Task Worker 2<br/>Port 20003]  
 end  
 end  
  
 subgraph "WORKER NODE 1"  
 subgraph "Infrastructure Ports "  
 NM\_W[Node Manager<br/>Port 10002]  
 OM\_W[Object Manager<br/>Port 10003]  
 MA\_W[Metrics Agent<br/>Port 10004]  
 RE\_W[Runtime Env Agent<br/>Port 10005]  
 end  
   
 subgraph "Worker Pool (20000-20100) "  
 A3[Actor 3<br/>Port 20000]  
 A4[Actor 4<br/>Port 20001]  
 TW3[Task Worker 3<br/>Port 20002]  
 TW4[Task Worker 4<br/>Port 20003]  
 end  
 end  
  
 Driver((Driver)) -->|6379| GCS  
 GCS -->|10002| NM\_H  
 GCS -->|10002| NM\_W  
 NM\_H -->|20000+| A1  
 NM\_W -->|20000+| A3  
 A1 -->|Direct| A3  
 OM\_H -->|Network| OM\_W  
  
 style GCS fill:#ff9999  
 style Driver fill:#99ccff  
 style A1 fill:#99ff99  
 style A3 fill:#99ff99  
 style TW1 fill:#ffcc99  
 style TW3 fill:#ffcc99

<details> <summary>📁 Text-based diagram (backup)</summary>

RAY CLUSTER PORT LAYOUT:  
  
HEAD NODE:  
┌─────────────────────────────────────────────────────────────┐  
│ HEAD NODE │  
├─────────────────────────────────────────────────────────────┤  
│ GCS Server: Port 6379 │  
│ Dashboard: Port 8265 │  
│ Ray Client Server: Port 10001 │  
│ Node Manager: Port 10002 │  
│ Object Manager: Port 10003 │  
│ Metrics Agent: Port 10004 │  
│ Runtime Env Agent: Port 10005 │  
│ │  
│ Worker Pool: Ports 20000-20100 (100 ports) │  
│ ├─ Actor 1: Port 20000 │  
│ ├─ Actor 2: Port 20001 │  
│ ├─ Task Worker 1: Port 20002 │  
│ └─ Task Worker 2: Port 20003 │  
└─────────────────────────────────────────────────────────────┘  
  
WORKER NODE 1:  
┌─────────────────────────────────────────────────────────────┐  
│ WORKER NODE 1 │  
├─────────────────────────────────────────────────────────────┤  
│ Node Manager: Port 10002 │  
│ Object Manager: Port 10003 │  
│ Metrics Agent: Port 10004 │  
│ Runtime Env Agent: Port 10005 │  
│ │  
│ Worker Pool: Ports 20000-20100 (100 ports) │  
│ ├─ Actor 3: Port 20000 │  
│ ├─ Actor 4: Port 20001 │  
│ ├─ Task Worker 3: Port 20002 │  
│ └─ Task Worker 4: Port 20003 │  
└─────────────────────────────────────────────────────────────┘  
  
COMMUNICATION FLOWS:  
Driver ──(6379)──→ GCS ──(10002)──→ Node Manager ──(20000+)──→ Workers  
 ↑ ↓  
 └──── Cluster State ───┘  
  
Worker ──(20000+)──→ Worker (Same Node: Direct)  
Worker ──(10003)───→ Object Manager ──(Network)──→ Object Manager ──(20000+)──→ Worker

</details>

### \*\*9. Visual Summary: Port Types and Usage Patterns\*\*

graph TB  
 subgraph "RAY PORT CATEGORIES"  
 subgraph "1. INFRASTRUCTURE PORTS (Fixed, 1 per node)"  
 IP[• GCS Port: 6379<br/>• Dashboard: 8265<br/>• Node Manager: 10002<br/>• Object Manager: 10003<br/>• Metrics Agent: 10004<br/>• Runtime Env Agent: 10005]  
 end  
  
 subgraph "2. WORKER PORTS (Dynamic, from shared pool)"  
 SPP[SHARED PORT POOL<br/>20000, 20001, 20002, 20003, ..., 20100]  
 SPP --> ACTORS[ACTORS<br/>Port: 1:1<br/>Lifetime: Long]  
 SPP --> TASKS[TASKS<br/>Port: N:1<br/>Lifetime: Short]  
 end  
  
 subgraph "3. PORT LIMITS"  
 LIMITS[Max Concurrent Ports = min:<br/>• Port Range Size: 100<br/>• num\_workers\_soft\_limit: 50<br/>• System FD Limit: 1024<br/>Result: 50 concurrent workers maximum]  
 end  
 end  
  
 style IP fill:#ffcccc  
 style SPP fill:#ccffcc  
 style ACTORS fill:#ccccff  
 style TASKS fill:#ffffcc  
 style LIMITS fill:#ffccff

<details> <summary>📁 Text-based diagram (backup)</summary>

┌─────────────────────────────────────────────────────────────────────────────┐  
│ RAY PORT CATEGORIES │  
├─────────────────────────────────────────────────────────────────────────────┤  
│ │  
│ 1. INFRASTRUCTURE PORTS (Fixed, 1 per node) │  
│ ┌─────────────────────────────────────────────────────────────────┐ │  
│ │ • GCS Port (6379) • Node Manager (10002) │ │  
│ │ • Dashboard (8265) • Object Manager (10003) │ │  
│ │ • Metrics Agent (10004) • Runtime Env Agent (10005) │ │  
│ └─────────────────────────────────────────────────────────────────┘ │  
│ │  
│ 2. WORKER PORTS (Dynamic, from shared pool) │  
│ ┌─────────────────────────────────────────────────────────────────┐ │  
│ │ SHARED PORT POOL │ │  
│ │ [20000, 20001, 20002, 20003, ..., 20100] │ │  
│ │ │ │ │  
│ │ ┌─────────────┴─────────────┐ │ │  
│ │ ▼ ▼ │ │  
│ │ ┌─ ACTORS ─┐ ┌─ TASKS ─┐ │ │  
│ │ │ Port: 1:1 │ │Port: N:1 │ │ │  
│ │ │ Lifetime: │ │Lifetime: │ │ │  
│ │ │ Long │ │ Short │ │ │  
│ │ └───────────┘ └──────────┘ │ │  
│ └─────────────────────────────────────────────────────────────────┘ │  
│ │  
│ 3. PORT LIMITS │  
│ ┌─────────────────────────────────────────────────────────────────┐ │  
│ │ Max Concurrent Ports = min( │ │  
│ │ Port Range Size, // e.g., 100 │ │  
│ │ num\_workers\_soft\_limit, // e.g., 50 │ │  
│ │ System FD Limit // e.g., 1024 │ │  
│ │ ) │ │  
│ │ Result: 50 concurrent workers maximum │ │  
│ └─────────────────────────────────────────────────────────────────┘ │  
└─────────────────────────────────────────────────────────────────────────────┘

</details>

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These Mermaid diagrams provide a modern, professional visualization of Ray's port allocation system while maintaining backward compatibility with the text-based versions. The diagrams will render beautifully in GitHub, GitLab, and most modern documentation platforms, while the collapsed text versions ensure the documentation works everywhere.