SPACE EFFICIENT PACKAGING FOR HORIZON FORBIDDEN WEST

STUDIOS GUERRILLA DECIMA

HORIZON FORBIDDEN WEST™

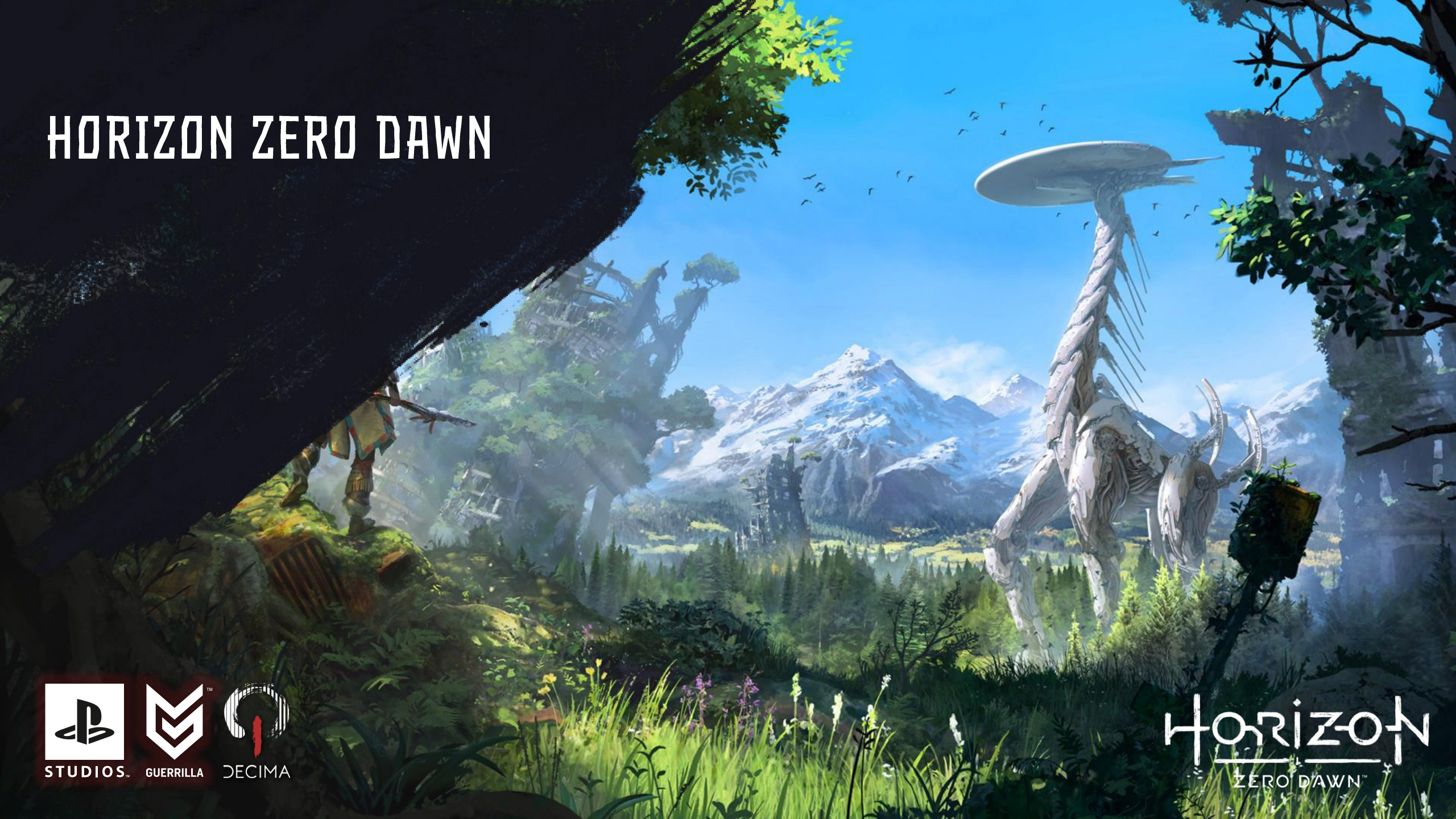
How we stopped worrying and love the algorithm.

CONTENTS

- Horizon Zero Dawn
- Content Graphs
- Horizon Forbidden West
- Algorithm
- Packaging

DECIMA™

HORIZON ZERO DAWN



INTRODUCTION

ISSUES WITH PREVIOUS SYSTEM

- The existing archive system was **error-prone and did not scale**
- Issues with **duplicates**, **missing content**, **expensive** processing
- Expected **asset re-use** for Horizon was going to complicate this
- Open world needed a **fundamentally different streaming system**

DESIGN GOALS

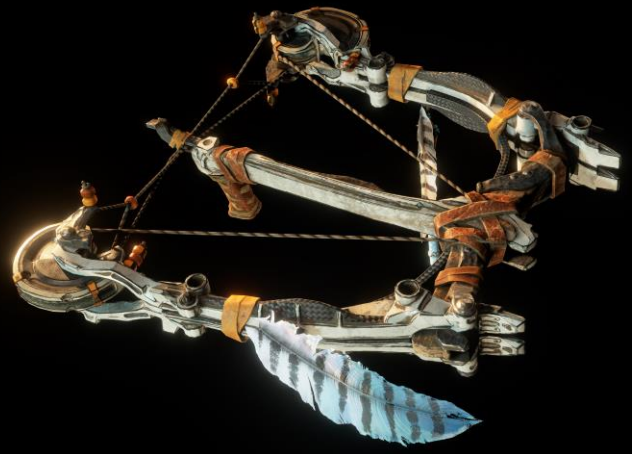
- **No loading screens**
- **No corridors** available
- **Continuous loading** around player
- **Faster iteration** by not packing data

RESULTS

- We ended production with **300,000 files**
- **Runtime streaming** of **individual files**
- Concatenated in **~2 GiB files for shipping** only
- Together, they **totaled about 45 GiB**

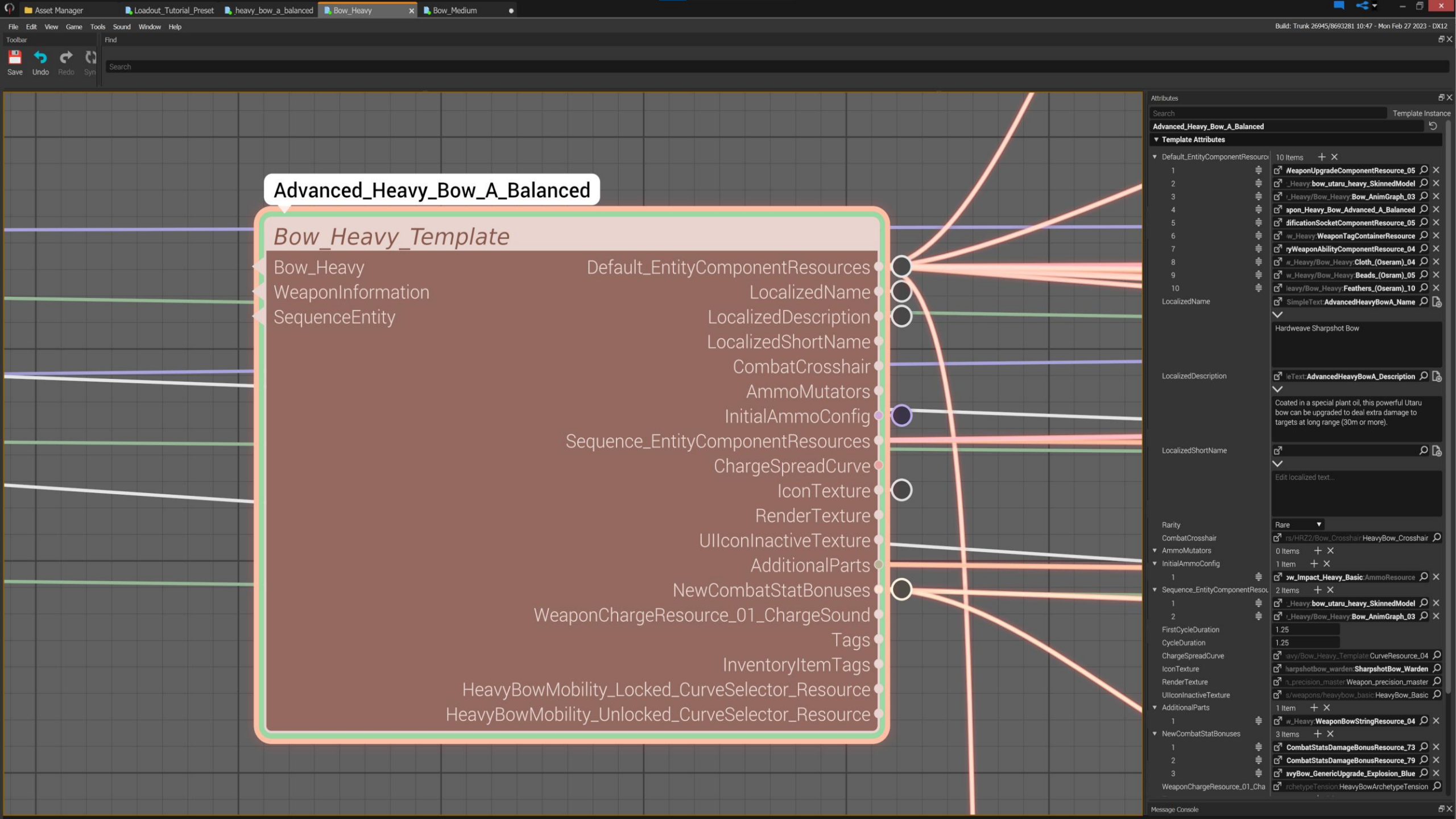
- Described in “Streaming the world of Horizon Zero Dawn”, 2017

CONTENT STRUCTURE





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heavy_bow_a_balanced
Bow_Heavy
Bow_Medium
File Edit View Game Tools Sound Window Help
Build: Trunk 26945/8693281 10:47 - Mon Feb 27 2023 - DX12
Toolbar
Save Undo Redo Syn
Find
Search
Advanced_Heavy_Bow_A_Balanced
Bow_Heavy_Template
Bow_Heavy
WeaponInformation
SequenceEntity
Default_EntityComponentResources
LocalizedName
LocalizedDescription
LocalizedShortName
CombatCrosshair
AmmoMutators
InitialAmmoConfig
Sequence_EntityComponentResources
ChargeSpreadCurve
IconTexture
RenderTexture
UIIconInactiveTexture
AdditionalParts
NewCombatStatBonuses
WeaponChargeResource_01_ChargeSound
Tags
InventoryItemTags
HeavyBowMobility_Locked_CurveSelector_Resource
HeavyBowMobility_Unlocked_CurveSelector_Resource
Attributes
Search
Template Instance
Advanced_Heavy_Bow_A_Balanced
Template Attributes
Default_EntityComponentResourc
10 Items
WeaponUpgradeComponentResource_05
_Heavy:bow_utaru_heavy_SkinnedModel
r_Heavy/Bow_Heavy:Bow_AnimGraph_03
apon_Heavy_Bow_Advanced_A_Balanced
dificationSocketComponentResource_05
w_Heavy:WeaponTagContainerResource
ryWeaponAbilityComponentResource_04
w_Heavy/Bow_Heavy:Cloth_(Oseram)_04
w_Heavy/Bow_Heavy:Beads_(Osram)_05
leavy/Bow_Heavy:Feathers_(Oseram)_10
LocalizedName
SimpleText:AdvancedHeavyBowA_Name
Hardweave Sharpshot Bow
LocalizedDescription
leText:AdvancedHeavyBowA_Description
Coated in a special plant oil, this powerful Utaru bow can be upgraded to deal extra damage to targets at long range (30m or more).
LocalizedShortName
Edit localized text...
Rarity
Rare
CombatCrosshair
rs/HRZ2/Bow_Crosshair:HeavyBow_Crosshair
AmmoMutators
0 Items
InitialAmmoConfig
1 Item
ow_Impact_Heavy_Basic:AmmoResource
Sequence_EntityComponentResou
2 Items
_Heavy:bow_utaru_heavy_SkinnedModel
r_Heavy/Bow_Heavy:Bow_AnimGraph_03
FirstCycleDuration
1.25
CycleDuration
1.25
ChargeSpreadCurve
avy/Bow_Heavy_Template:CurveResource_04
IconTexture
harpshotbow_warden:SharpshotBow_Warden
RenderTexture
n_precision_master:Weapon_precision_master
UIIconInactiveTexture
s/weapons/heavybow_basic:HeavyBow_Basic
AdditionalParts
1 Item
w_Heavy:WeaponBowStringResource_04
NewCombatStatBonuses
3 Items
CombatStatsDamageBonusResource_73
CombatStatsDamageBonusResource_79
avyBow_GenericUpgrade_Explosion_Blue
WeaponChargeResource_01_Cha
rchetypeTension:HeavyBowArchetypeTension
Message Console

Asset Manager | Loadout_Tutorial_Preset | heavy_bow_a_balanced | Bow_Heavy | Bow_Medium

File Edit View Game Tools Sound Window Help

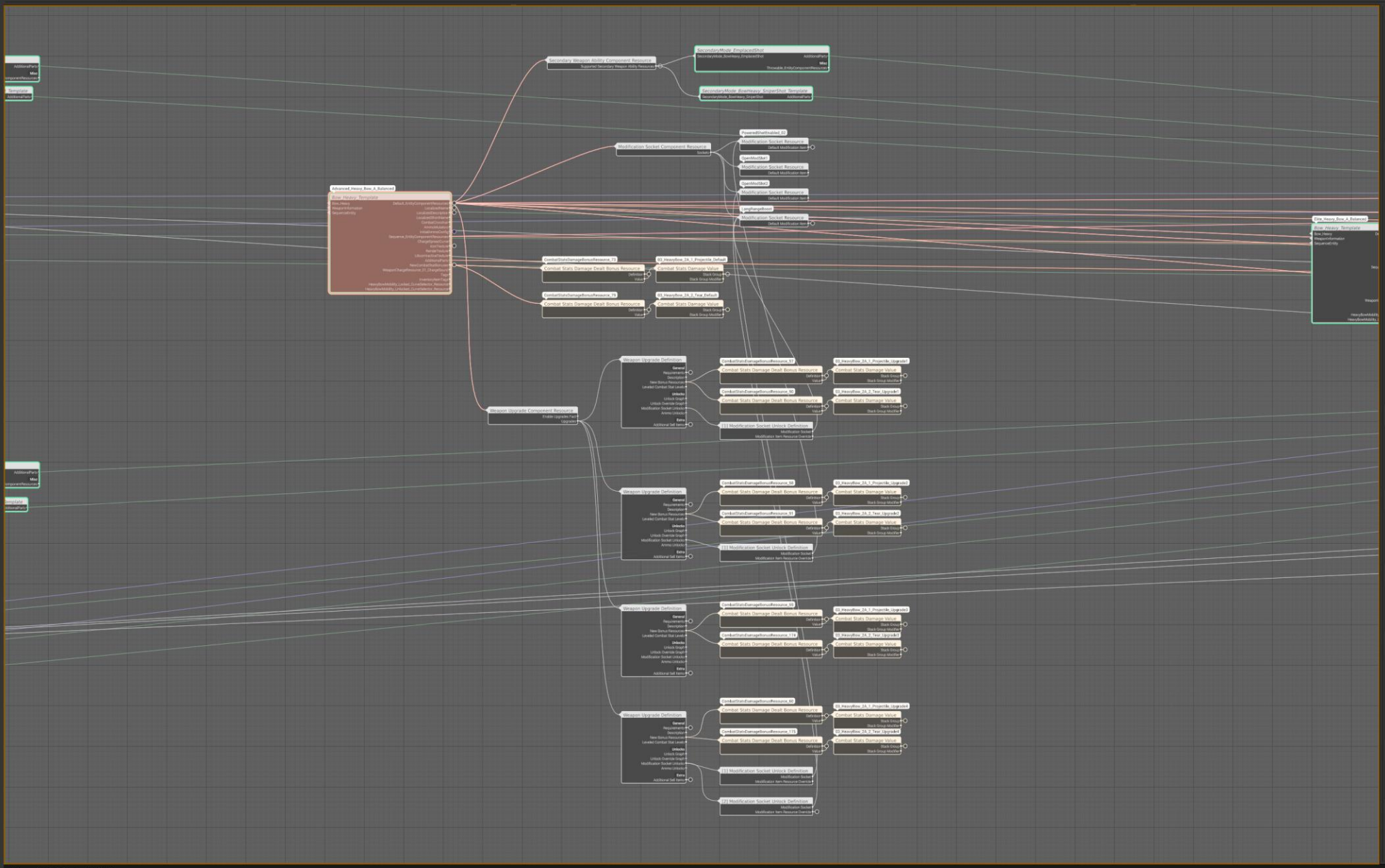
Build: Trunk 26945/8693281 10:47 - Mon Feb 27 2023 - DX12

Toolbar

Save Undo Redo Syn

Find

Search



Attributes

Search

Template Instance

Advanced_Heavy_Bow_A_Balanced

Template Attributes

Default_EntityComponentResourc	10 Items
1	WeaponUpgradeComponentResource_05
2	_Heavy:bow_utaru_heavy_SkinnedModel
3	r_Heavy/Bow_Heavy:Bow_AnimGraph_03
4	apon_Heavy_Bow_Advanced_A_Balanced
5	dificationSocketComponentResource_05
6	w_Heavy:WeaponTagContainerResource
7	ryWeaponAbilityComponentResource_04
8	w_Heavy/Bow_Heavy:Cloth_(Oseram)_04
9	w_Heavy/Bow_Heavy:Beads_(Oseram)_05
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CycleDuration	1.25
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RenderTexture	_precision_master:Weapon_precision_master
UIIconInactiveTexture	s/weapons/heavybow_basic:HeavyBow_Basic
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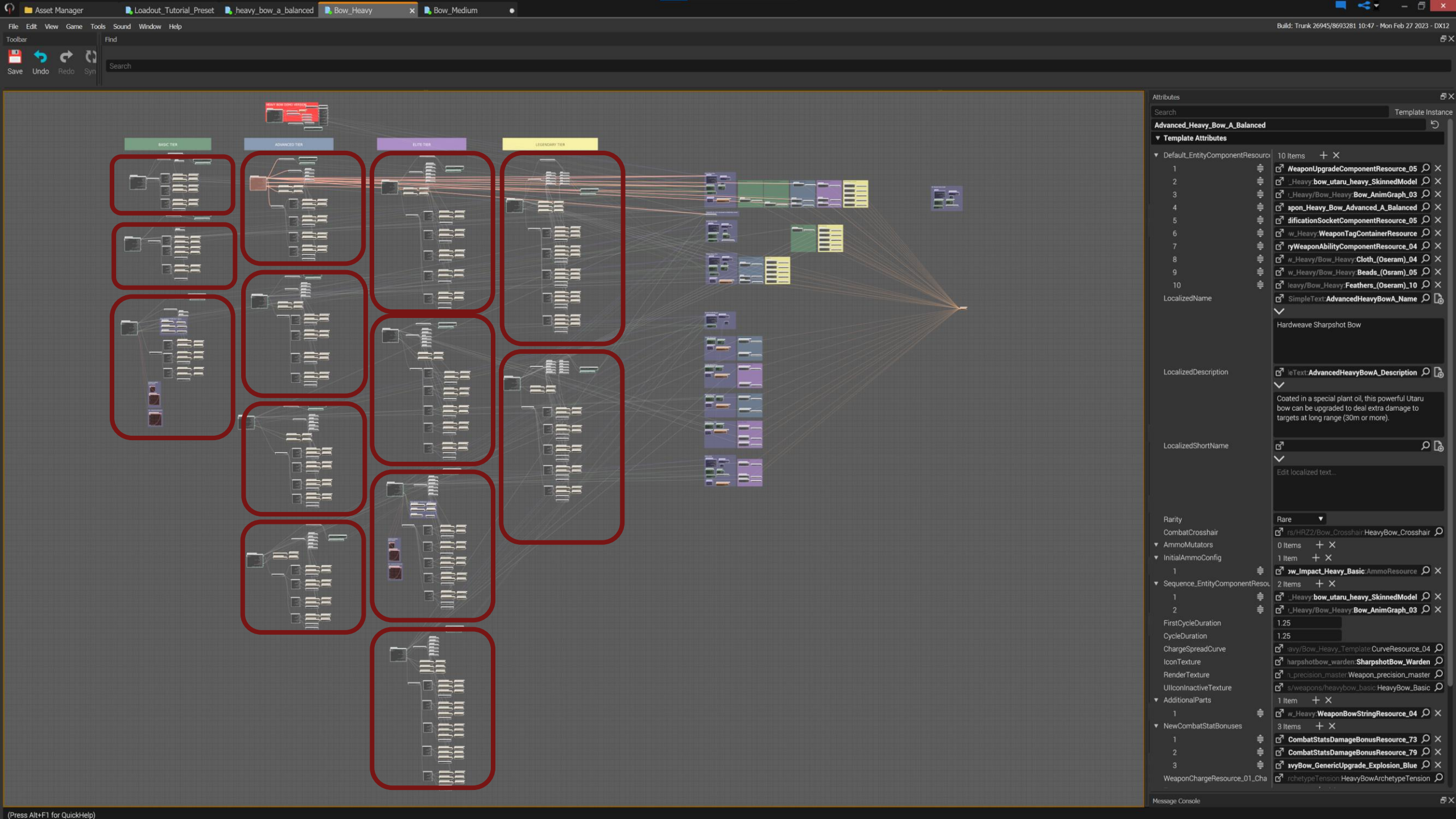
(Press Alt+F1 for QuickHelp)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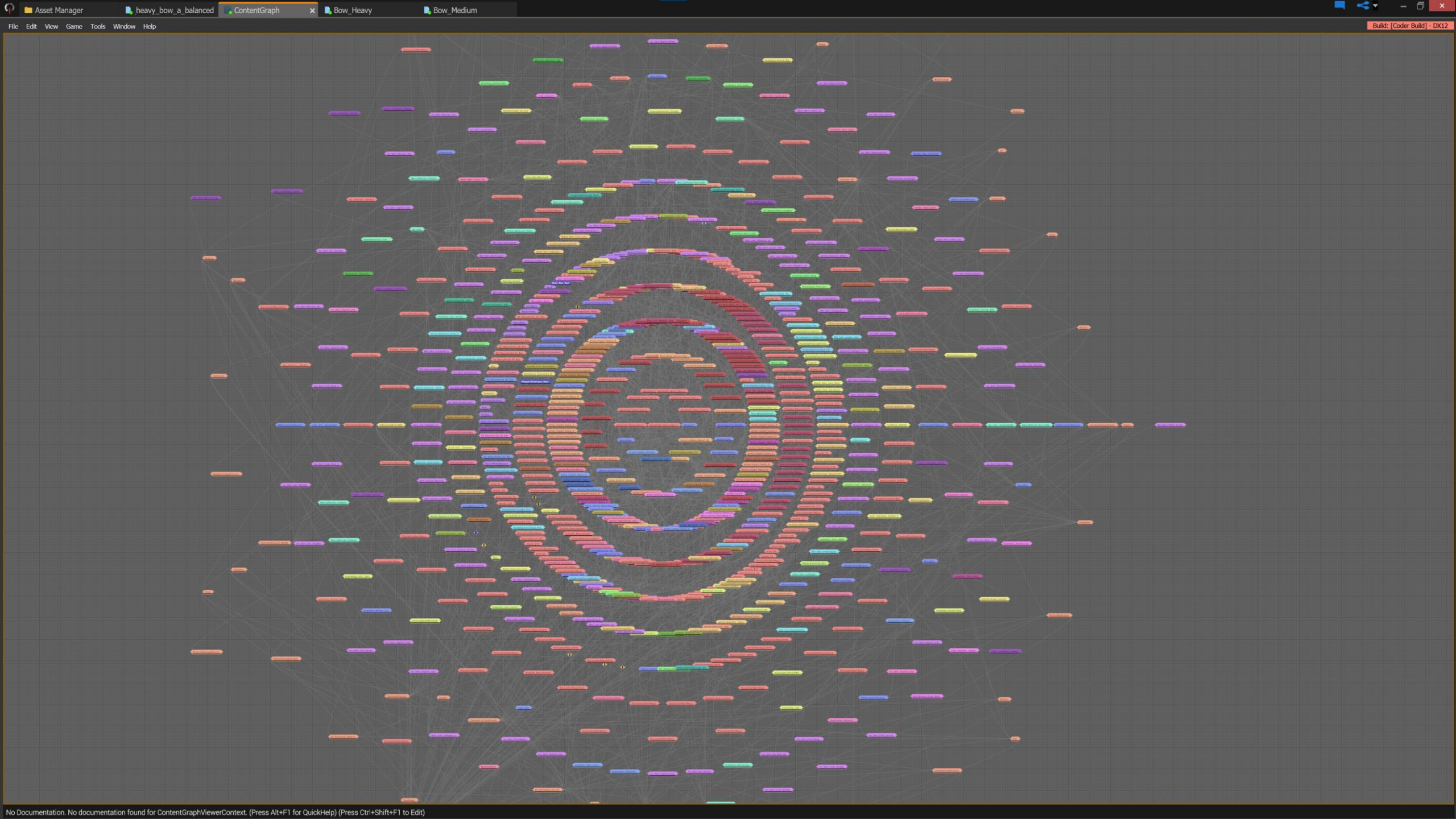
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ContentGraph
Bow_Heavy
Bow_Medium
File
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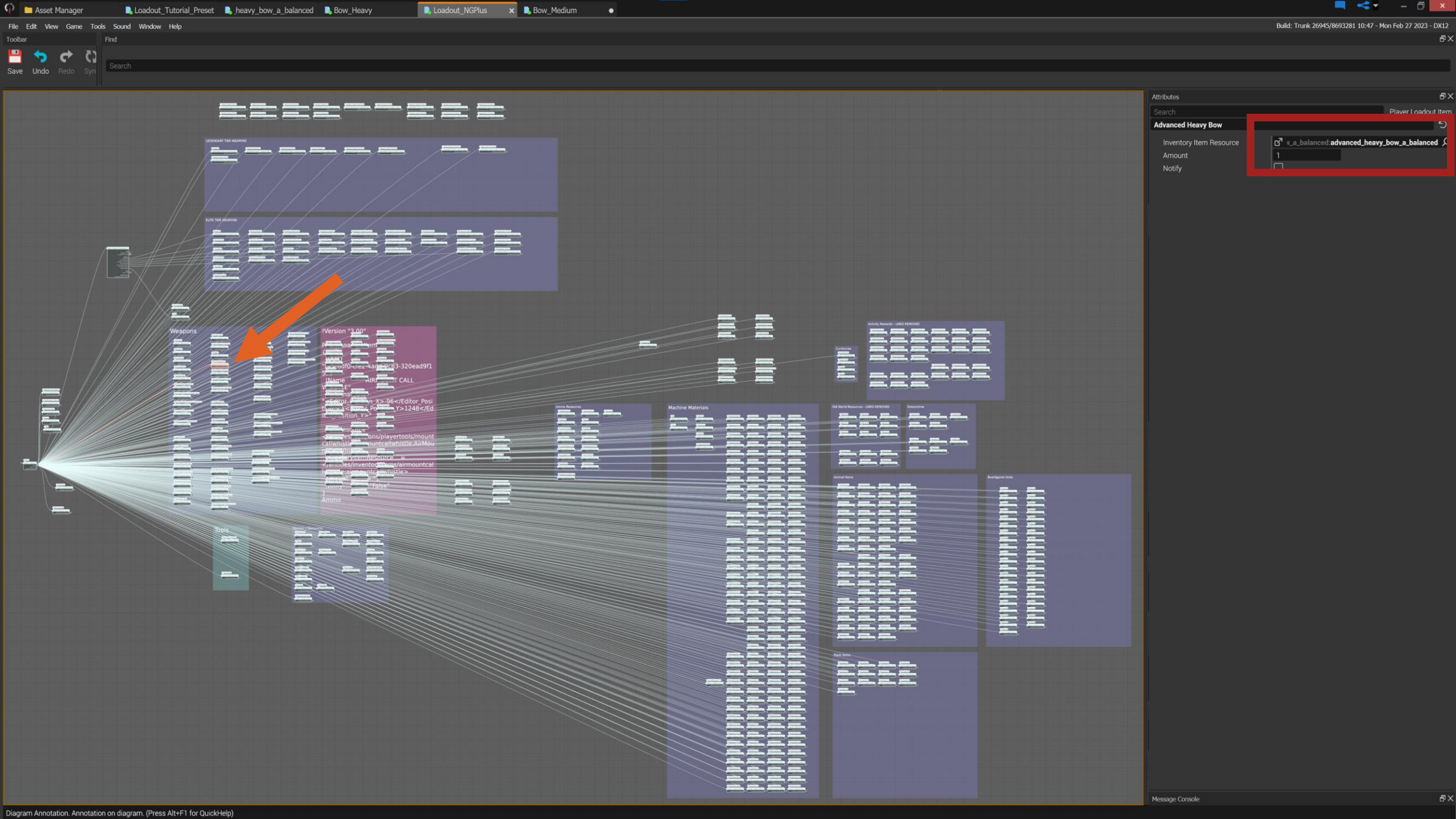
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Bow_Heavy
Loadout_NGPlus
Bow_Medium
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Toolbar
Save
Undo
Redo
Find
Search
Attributes
Search
Player Loadout Item
Advanced Heavy Bow
Inventory Item Resource
v_a_balanced:advanced_heavy_bow_a_balanced
Amount
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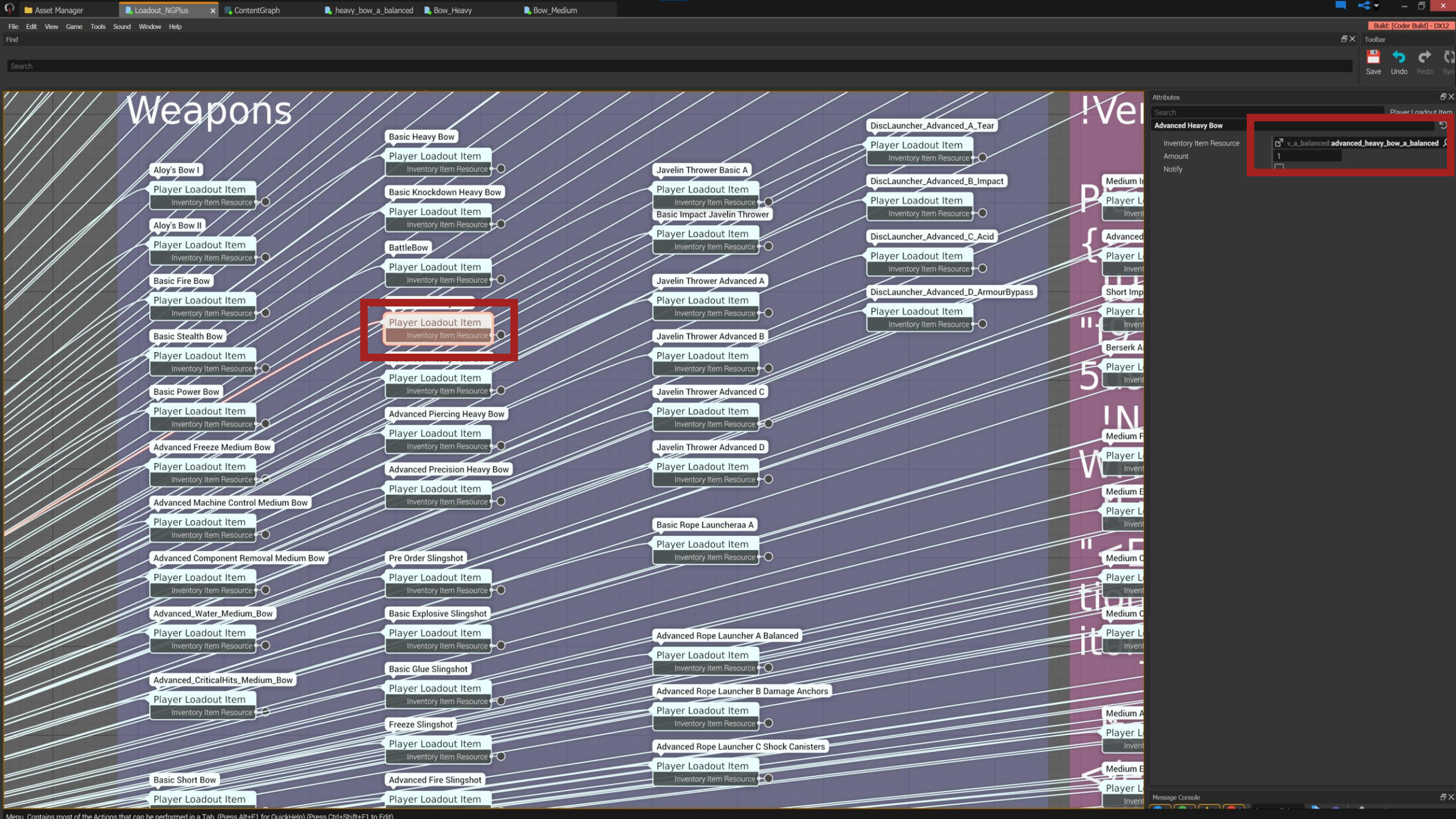
Notify
Weapons
Tools
Ammo
Machine Materials
Message Console
Diagram Annotation. Annotation on diagram. (Press Alt+F1 for QuickHelp)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Loadout_NGPlus
ContentGraph
heavy_bow_a_balanced
Bow_Heavy
Bow_Medium
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Find
Search
Build: [Coder Build] - DX12
Toolbar
Save
Undo
Redo
Weapons
Aloy's Bow I
Aloy's Bow II
Basic Fire Bow
Basic Stealth Bow
Basic Power Bow
Advanced Freeze Medium Bow
Advanced Machine Control Medium Bow
Advanced Component Removal Medium Bow
Advanced_Water_Medium_Bow
Advanced_CriticalHits_Medium_Bow
Basic Short Bow
Basic Heavy Bow
Basic Knockdown Heavy Bow
BattleBow
Advanced Piercing Heavy Bow
Advanced Precision Heavy Bow
Pre Order Slingshot
Basic Explosive Slingshot
Basic Glue Slingshot
Freeze Slingshot
Advanced Fire Slingshot
Javelin Thrower Basic A
Basic Impact Javelin Thrower
Javelin Thrower Advanced A
Javelin Thrower Advanced B
Javelin Thrower Advanced C
Javelin Thrower Advanced D
Basic Rope Launcheraa A
Advanced Rope Launcher A Balanced
Advanced Rope Launcher B Damage Anchors
Advanced Rope Launcher C Shock Canisters
DiscLauncher_Advanced_A_Tear
DiscLauncher_Advanced_B_Impact
DiscLauncher_Advanced_C_Acid
DiscLauncher_Advanced_D_ArmourBypass
Player Loadout Item
Inventory Item Resource
Attributes
Search
Player Loadout Item
Advanced Heavy Bow
Inventory Item Resource
v_a_balanced:advanced_heavy_bow_a_balanced
Amount
1
Notify
Message Console
Menu. Contains most of the Actions that can be performed in a Tab. (Press Alt+F1 for QuickHelp) (Press Ctrl+Shift+F1 to Edit)

```
/**
@brief RTTI for PlayerLoadout
**/
RTTI_START_COMPOUND(PlayerLoadout, RTTISET_REFCOUNT_AND_STREAMINGREF) //! DisplayCategory="Loadout" DisplayColor="LightCyan"
    RTTI_CONCRETE(PlayerLoadout)
    RTTI_VERSION(PlayerLoadout, 3)

    RTTI_START_ATTRS(PlayerLoadout)
        RTTI_ATTR(PlayerLoadout,     "ClearInventory",                RTTI_OF(bool),                          mClearInventory,
        RTTI_ATTR(PlayerLoadout,     "ClearPerks",                    RTTI_OF(bool),                          mClearPerks,
        RTTI_ATTR_MIN(PlayerLoadout,"UnspentPerkPoints",              RTTI_OF(int),                           mUnspentPerkPoints,
        RTTI_ATTR(PlayerLoadout,     "Entries",                       RTTI_OF(Array_Ref_PlayerLoadoutEntry),  mEntries,
        RTTI_ATTR(PlayerLoadout,     "EquipConfig",                   RTTI_OF(PlayerEquipConfiguration),      mEquipConfig,
        RTTI_ATTR(PlayerLoadout,     "LoadoutDescription",            RTTI_OF(Ref_LocalizedTextResource),     mLoadoutDescription,
        RTTI_ATTR(PlayerLoadout,     "DuplicateStackablesToOverflow", RTTI_OF(bool),                          mDuplicateStackablesToO
    RTTI_END_ATTRS(PlayerLoadout)

    RTTI_START_EXPORTED_SYMBOLS(PlayerLoadout)
    RTTI_END_EXPORTED_SYMBOLS(PlayerLoadout)

RTTI_END_COMPOUND(PlayerLoadout)
```

```
/**
@brief RTTI for PlayerLoadoutItem
**/
RTTI_START_COMPOUND(PlayerLoadoutItem, RTTISET_REFCOUNT) //! DisplayCategory="Loadout" DisplayColor="LightCyan"
    RTTI_CONCRETE(PlayerLoadoutItem)
    RTTI_VERSION(PlayerLoadoutItem, 1)

    RTTI_START_ATTRS(PlayerLoadoutItem)
#ifdef _CONVERSION_CODE
        RTTI_ATTR(PlayerLoadoutItem,        "ItemResource",          RTTI_OF(StreamingRef_EntityResource),          mItemResource,
#endif // _CONVERSION_CODE
        RTTI_ATTR(PlayerLoadoutItem,        "InventoryItemResource", RTTI_OF(StreamingRef_InventoryItemResource),   mInventoryItemResource,
        RTTI_ATTR_MIN(PlayerLoadoutItem,    "Amount",                RTTI_OF(int),                                  mAmount,        1,
        RTTI_ATTR(PlayerLoadoutItem,        "Notify",                RTTI_OF(bool),                                 mNotify,
    RTTI_END_ATTRS(PlayerLoadoutItem)

RTTI_END_COMPOUND(PlayerLoadoutItem)
```

ROOT OBJECTS

- **Tiles, Weapons, Outfits, Entities**
- **Top-level objects**
- **Requested directly** by high-level systems
- **Lifetime managed externally**
- **Identified as targets of streaming references**

REGULAR OBJECTS

- **Meshes, textures, behavior**
- Loaded together with **root objects**
- **Never requested directly**
- **Lifetime** managed by **streaming system**
- Based on **lifetime of root objects**

HORIZON FORBIDDEN WEST

WHAT HAD WE LEARNED?

- Many files contained **multiple assets**
- Some files contained **unused assets**
- These would **link to other files** again
- **300 MiB** memory used
- **Overreading of unnecessary files**

FILE-BASED CONTENT

- Problems with **loading granularity**
- **Common problem** in many game engines
- Default for **DCC packages** such as Maya
- Default for revision control systems
- And works well for **artists, designers**

FORBIDDEN WEST DESIGN GOALS

We **knew what we wanted**:

- **Let artists work** how they want
- **File-based** content setup should **not dictate streaming**
- Packaging should be **fully automated**
- **Overreading** should be **minimized or eliminated**

OBJECT BASED STREAMING

- We have a **fully connected content graph**
- **All objects** can be found from **a single root**
- This let us **analyze the object graph** in detail
- Find a way to **stream object graphs**

PACKAGING ALGORITHM

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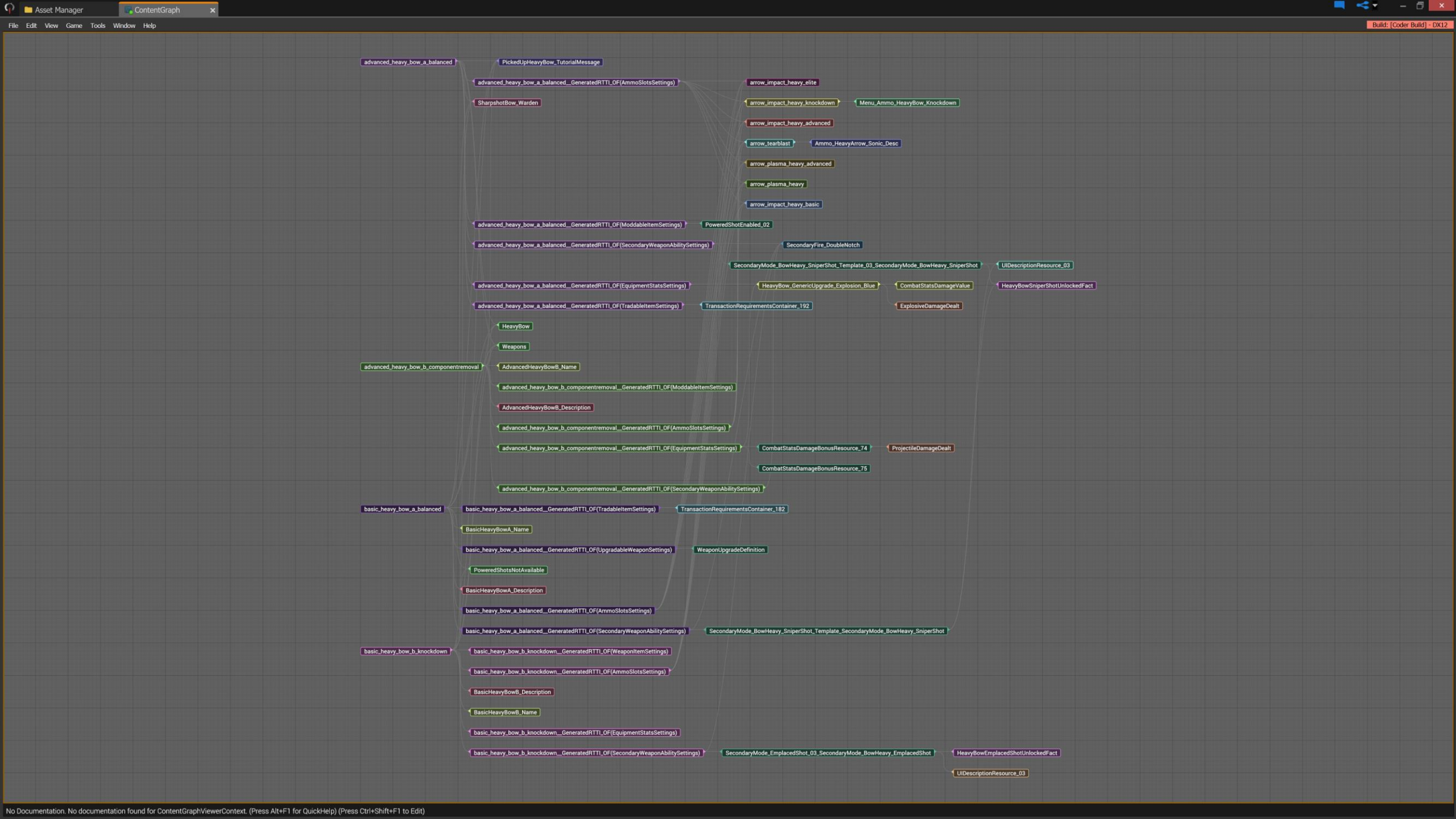
HORIZON II FORBIDDEN WEST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PickedUpHeavyBow_TutorialMessage
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arrow_impact_heavy_elite
SharpshotBow_Warden
arrow_impact_heavy_knockdown
Menu_Ammo_HeavyBow_Knockdown
arrow_impact_heavy_advanced
arrow_tearblast
Ammo_HeavyArrow_Sonic_Desc
arrow_plasma_heavy_advanced
arrow_plasma_heavy
arrow_impact_heavy_basic
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HeavyBow
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CombatStatsDamageBonusResource_75
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BasicHeavyBowA_Description
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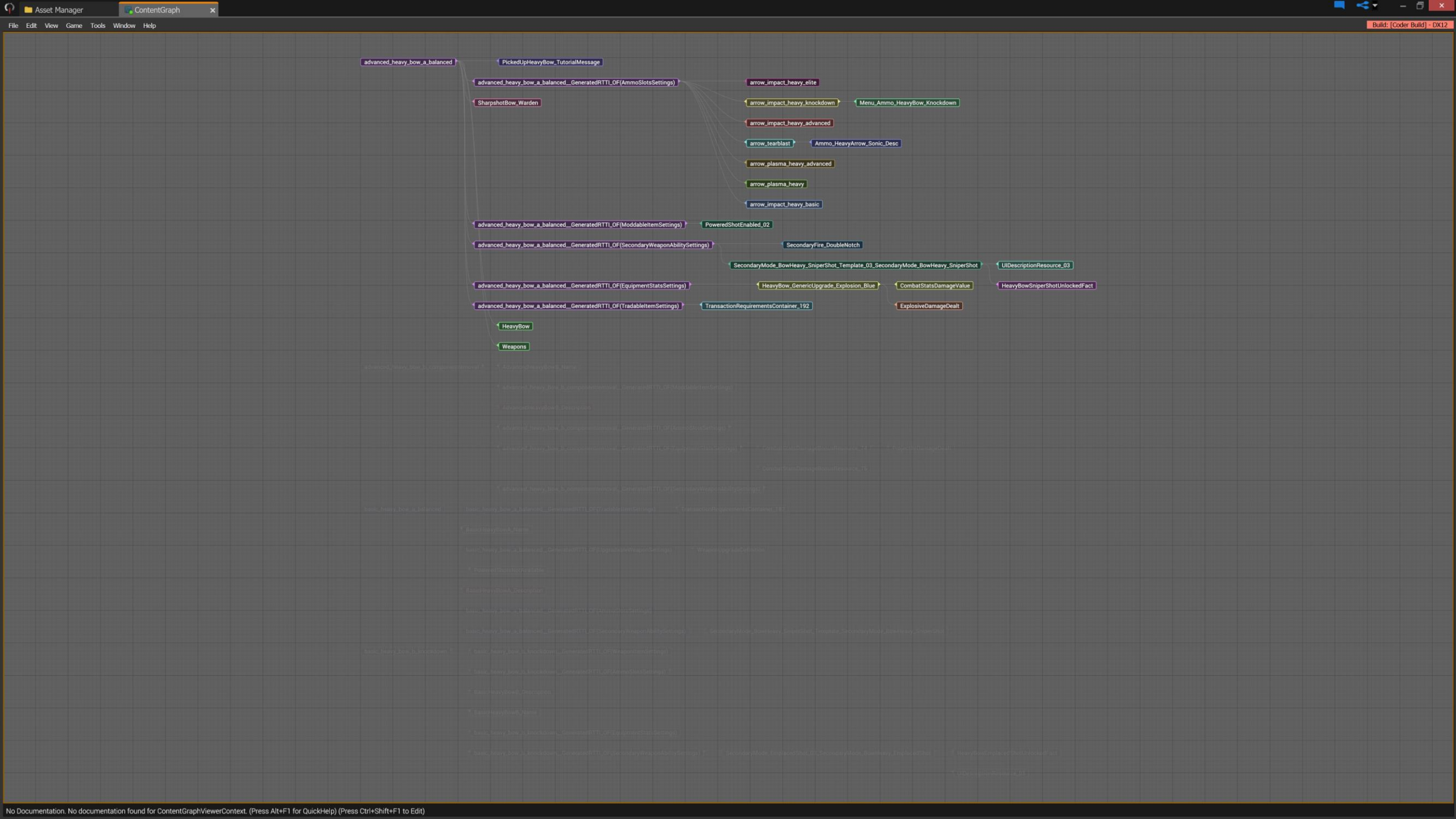
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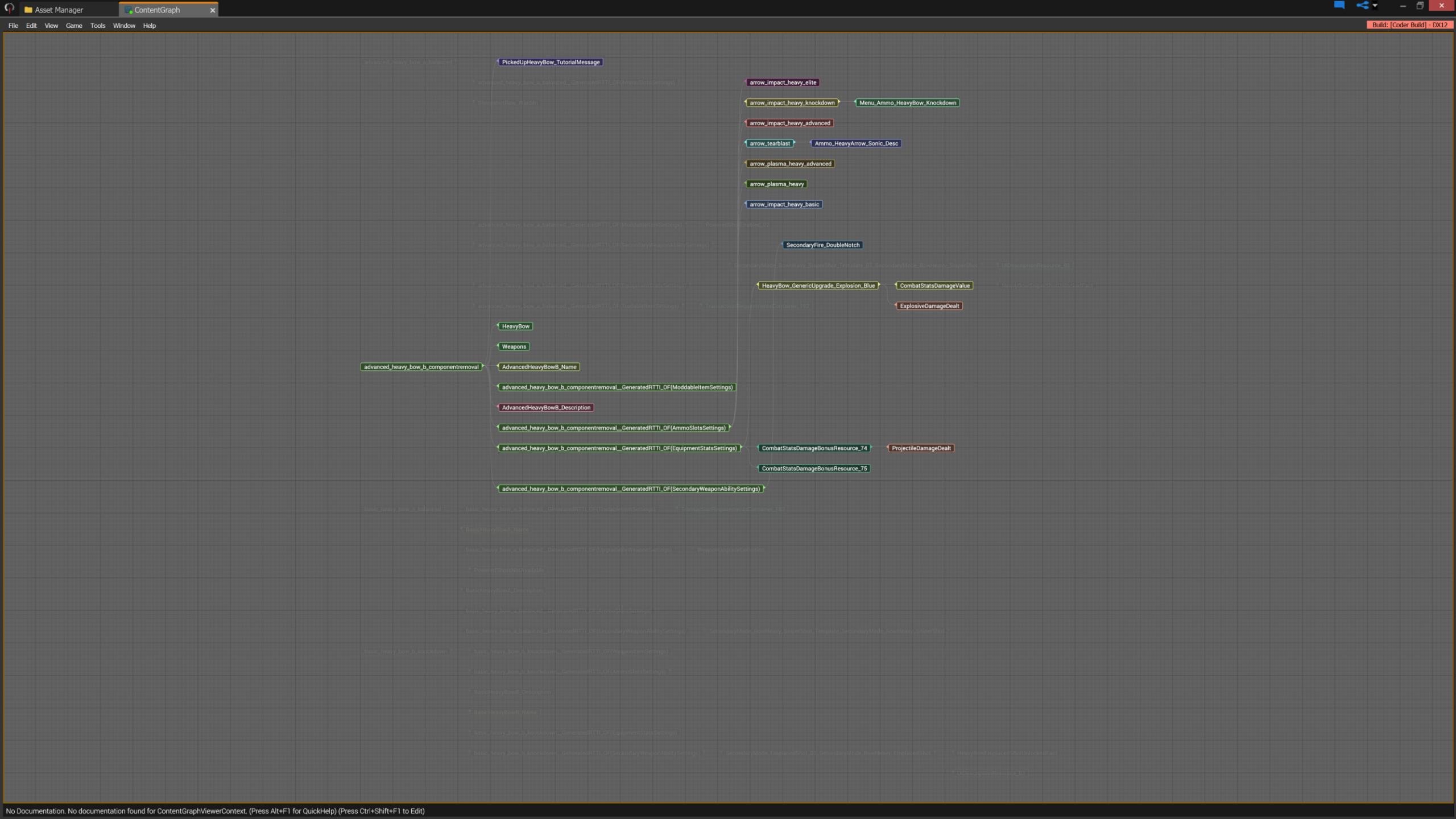
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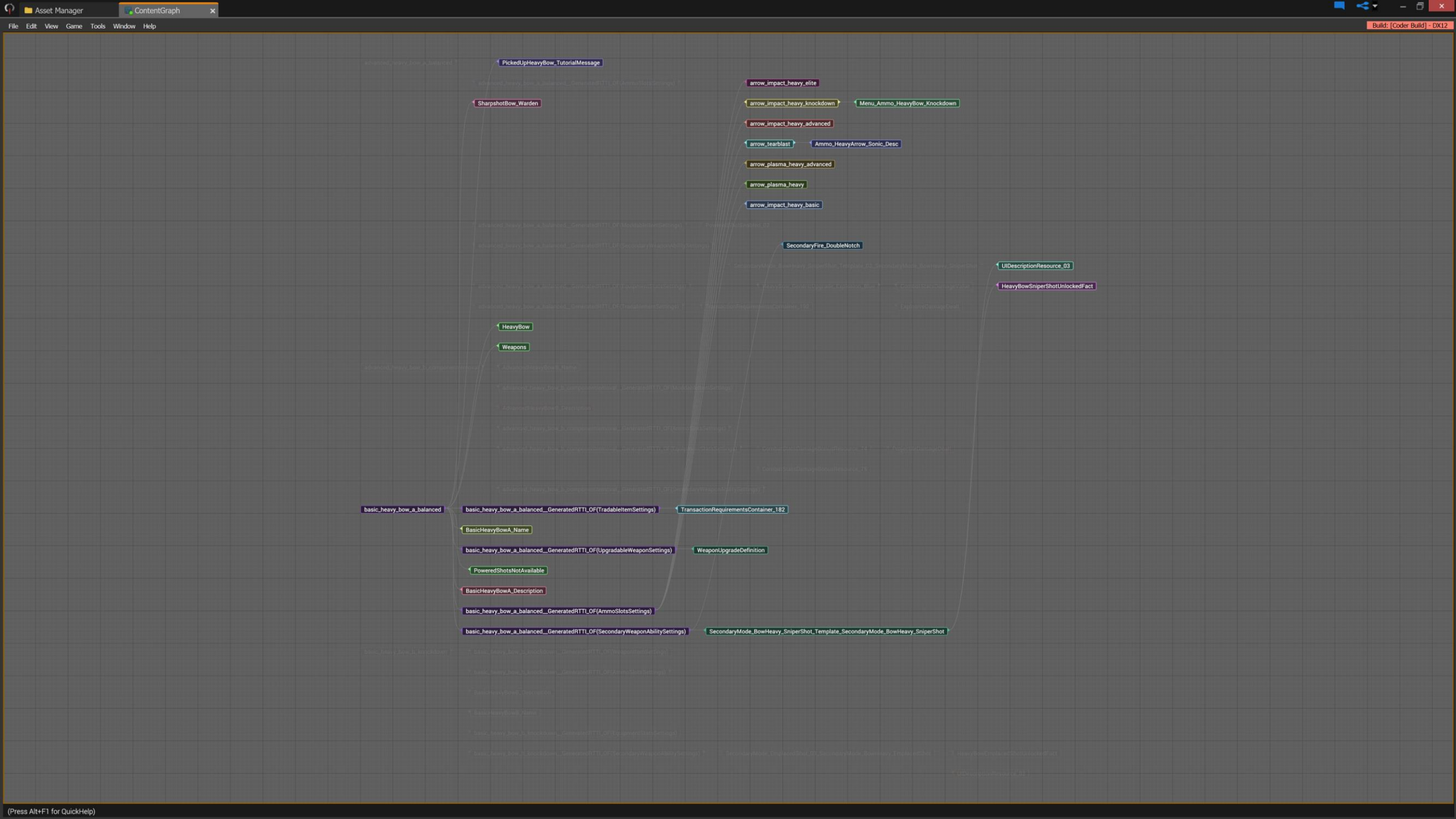
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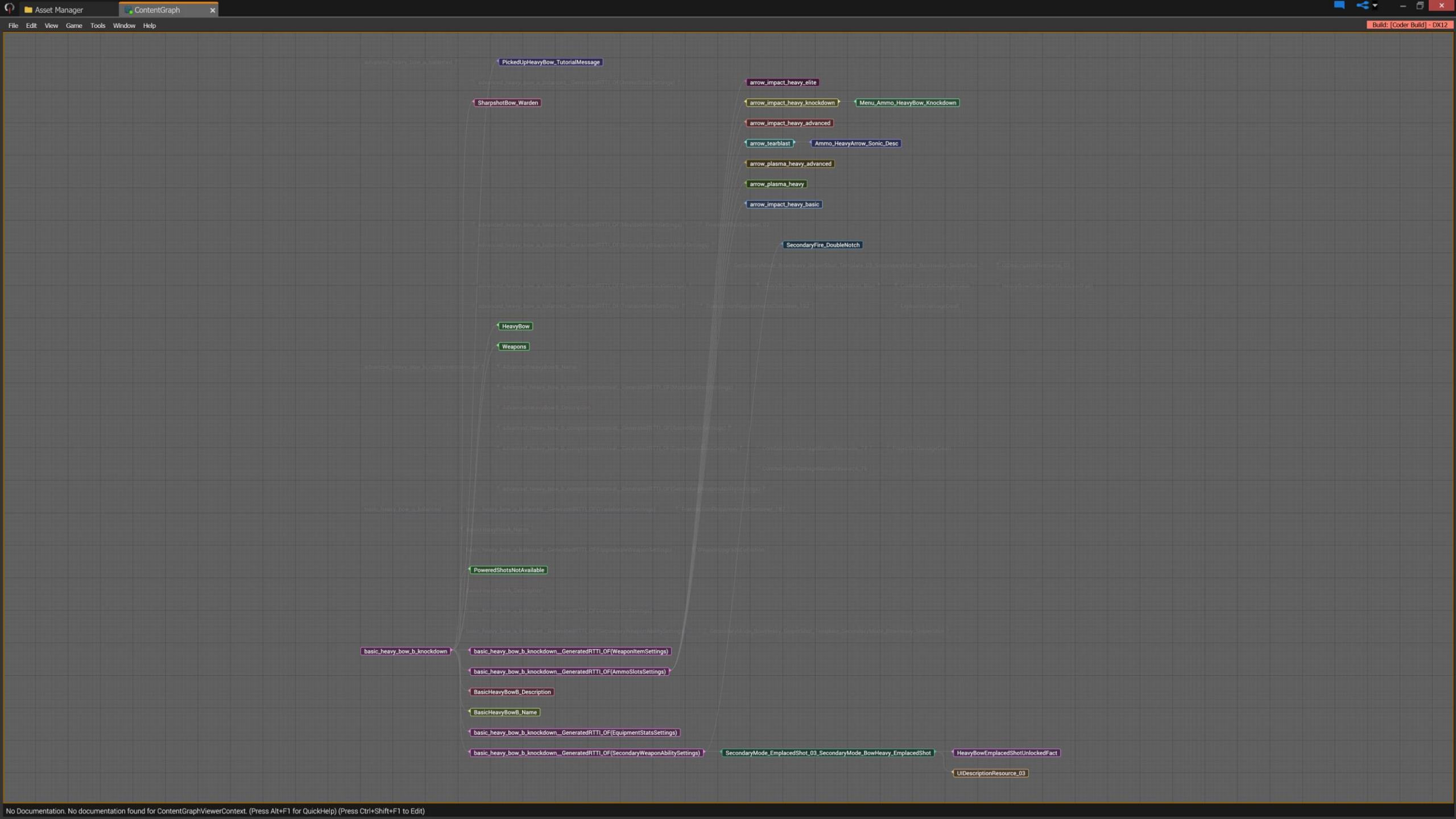
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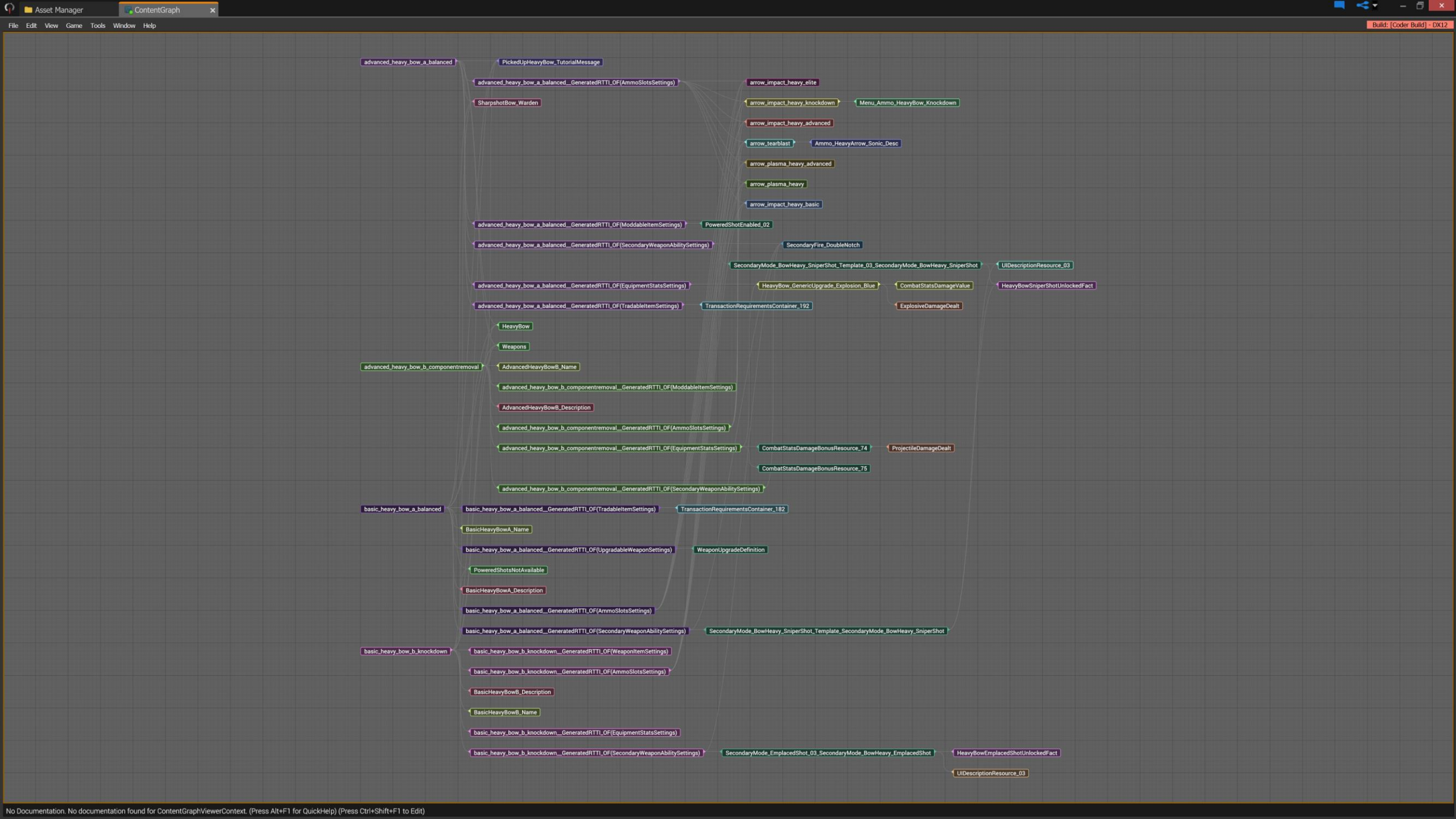
PACKAGING ALGORITHM PHASES

1. Building an **object graph**
2. Object graph **labelling**
3. Building the **group graph**

PHASE 1: GRAPH GENERATION

- **Traverse object graph** for each root
- **Generate a node** for each object we encounter
- **Setup links between objects**
- **Mark as root or regular object**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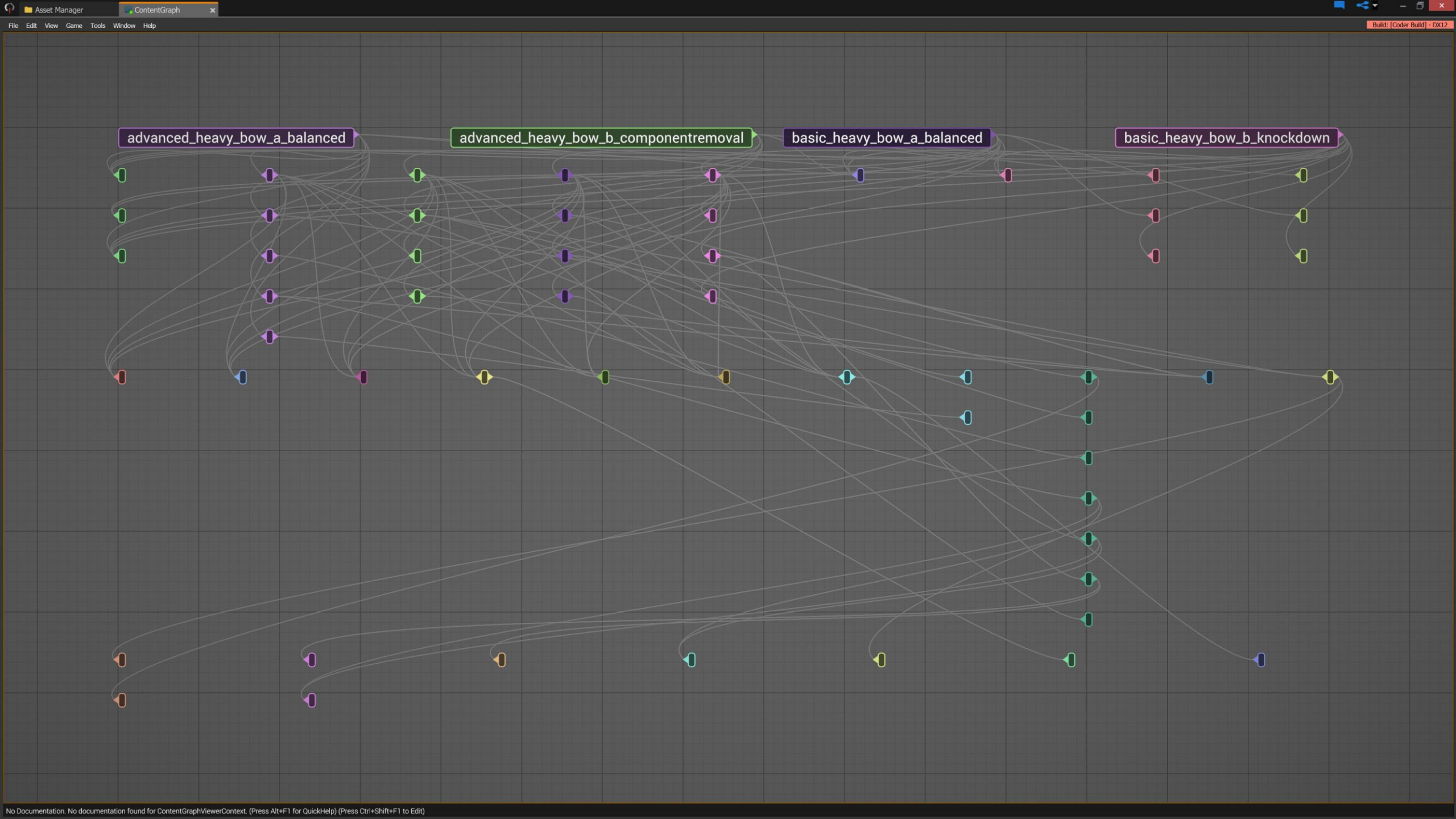
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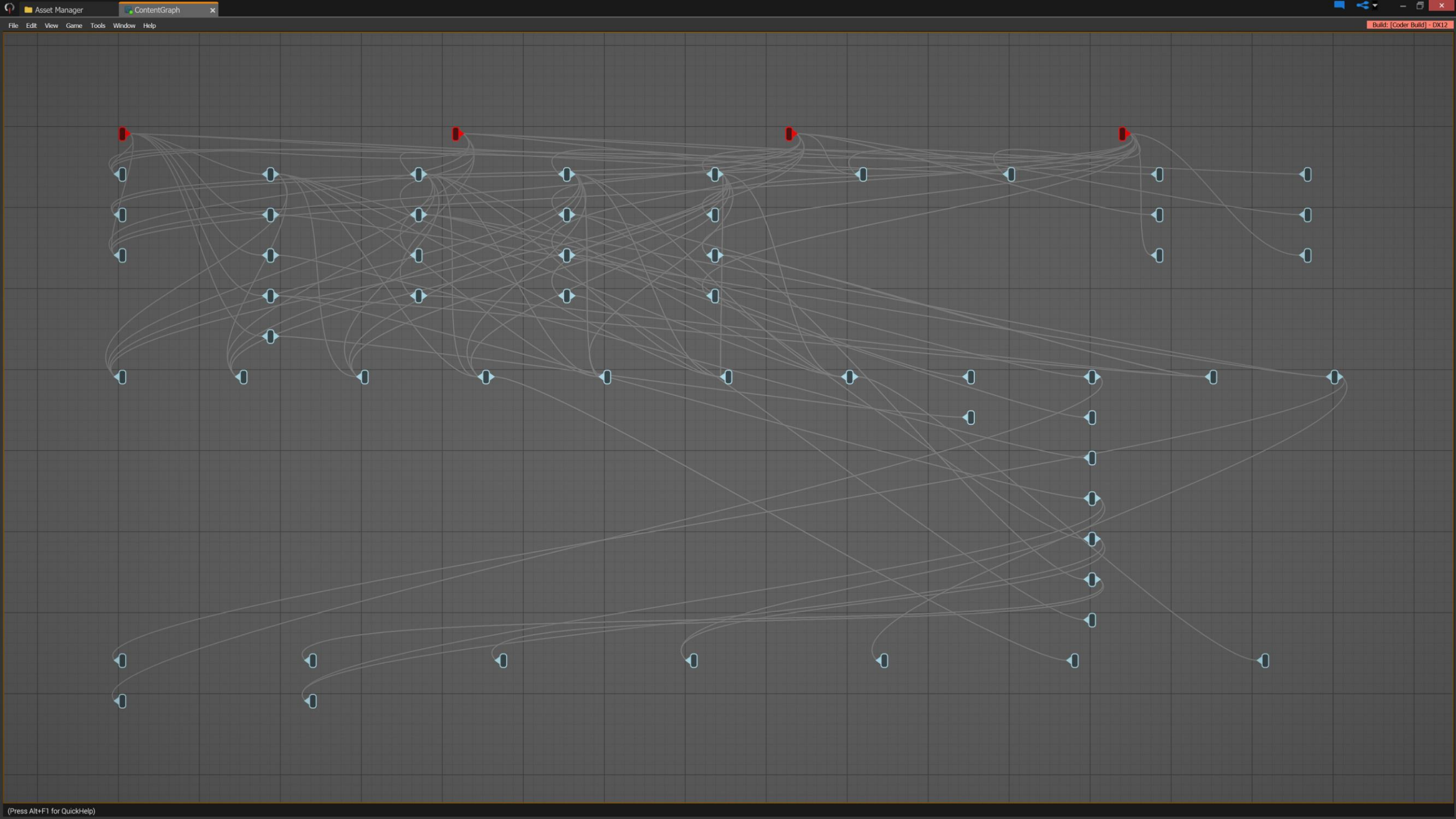
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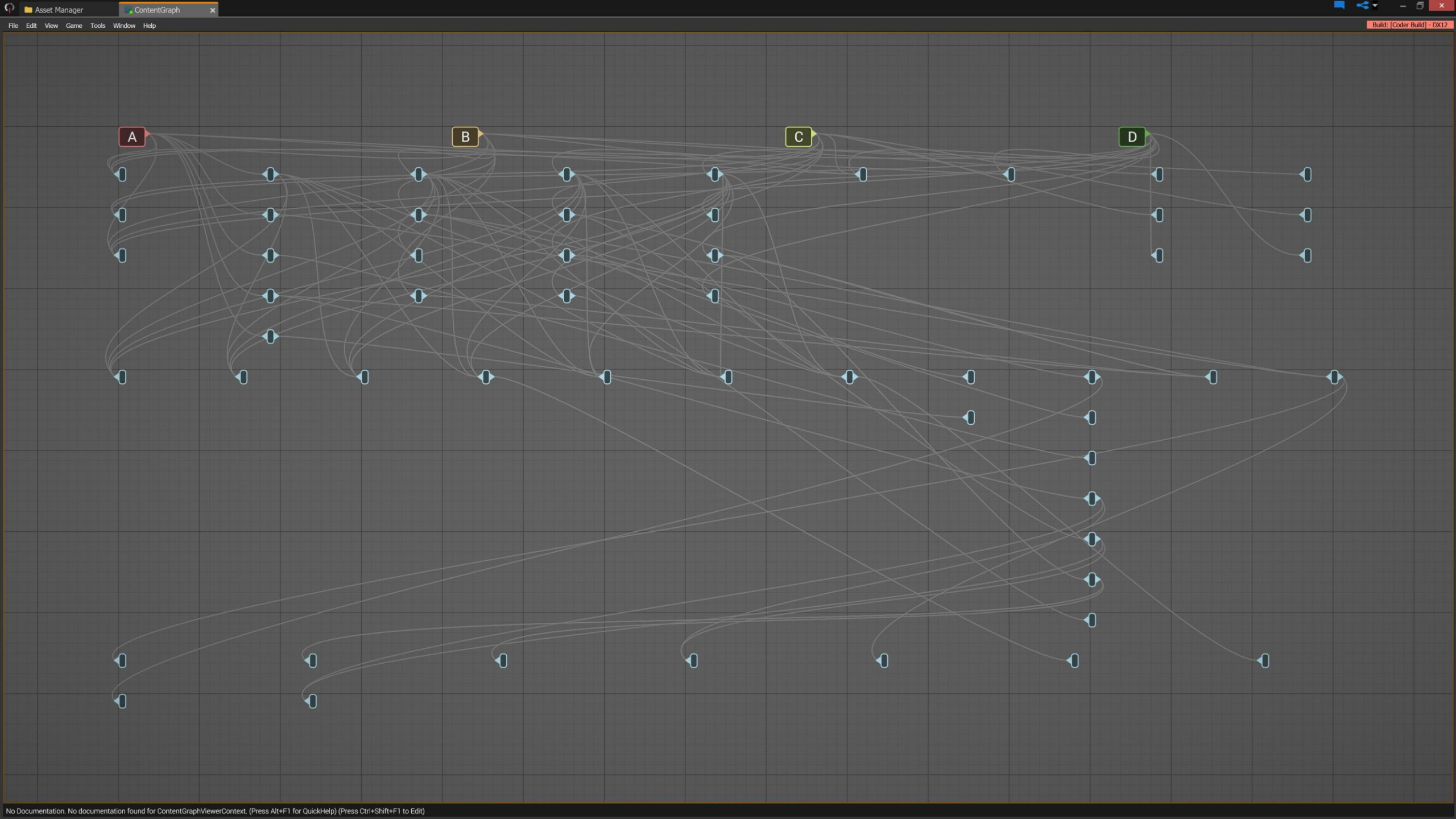
GRAPH LABELING

- Give each **root object** a **unique identifier**
- Start **graph traversal at each root object**
- Traverse all **required links**
- **Add the unique identifier** to **each object**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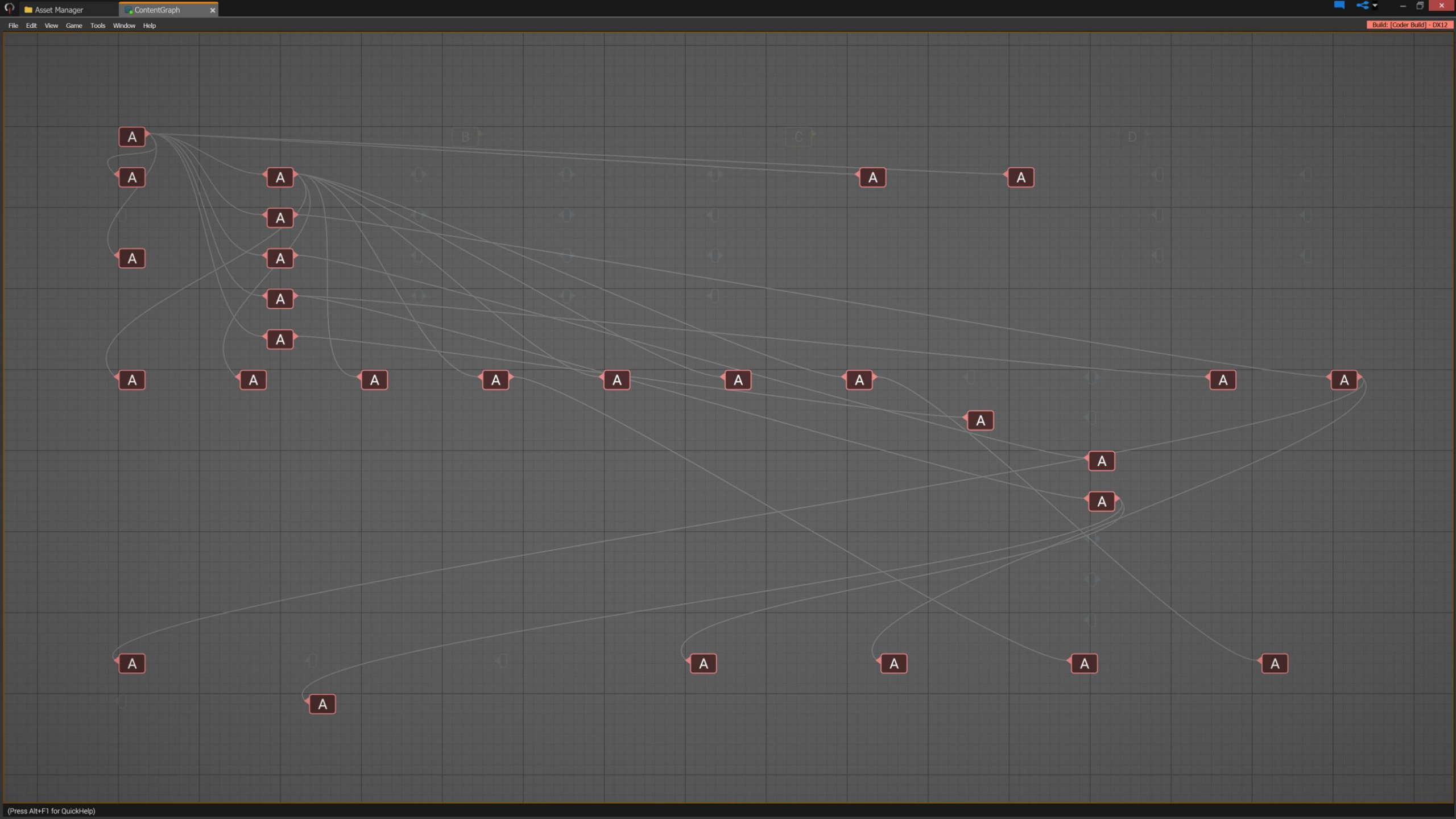
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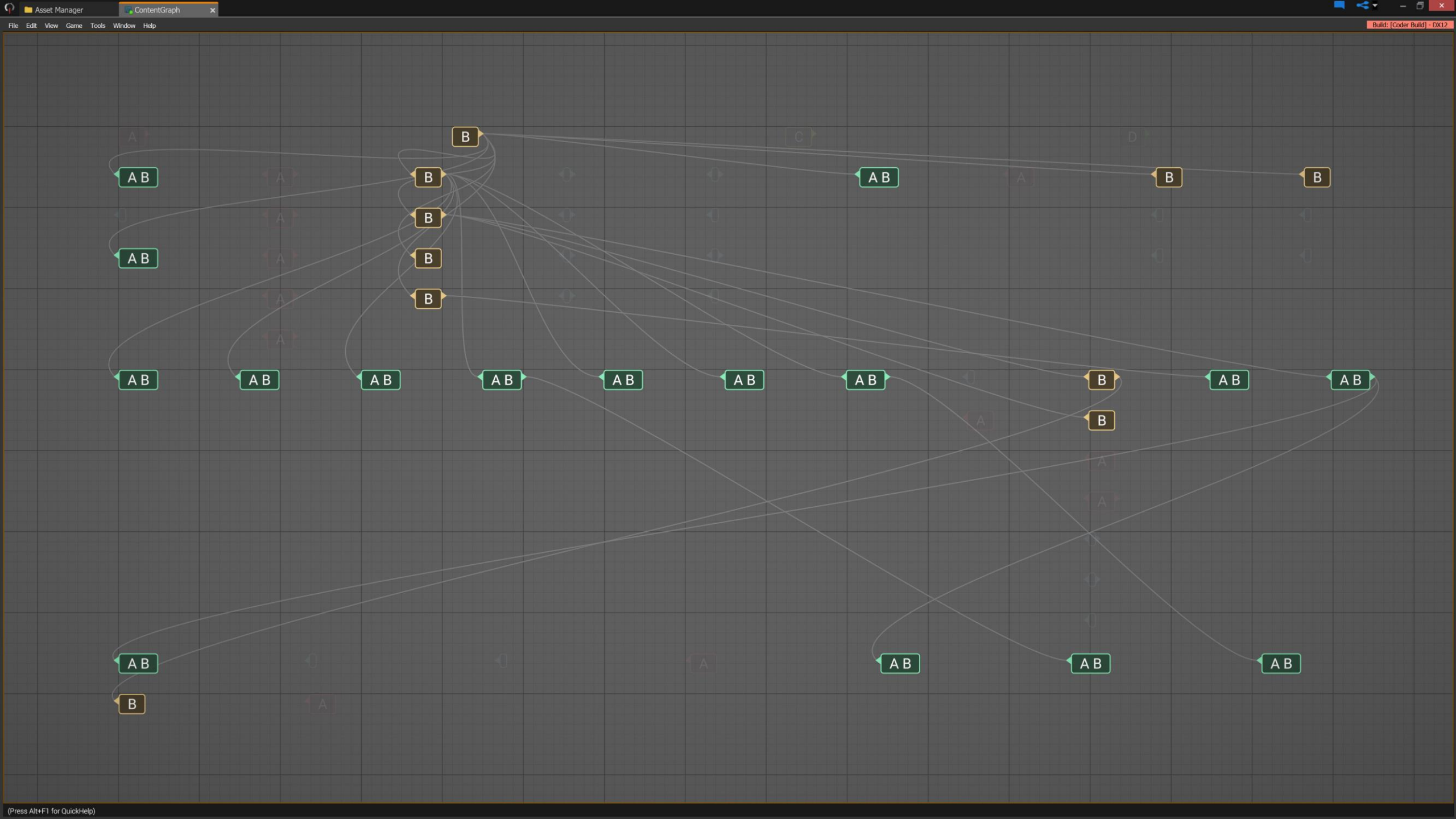
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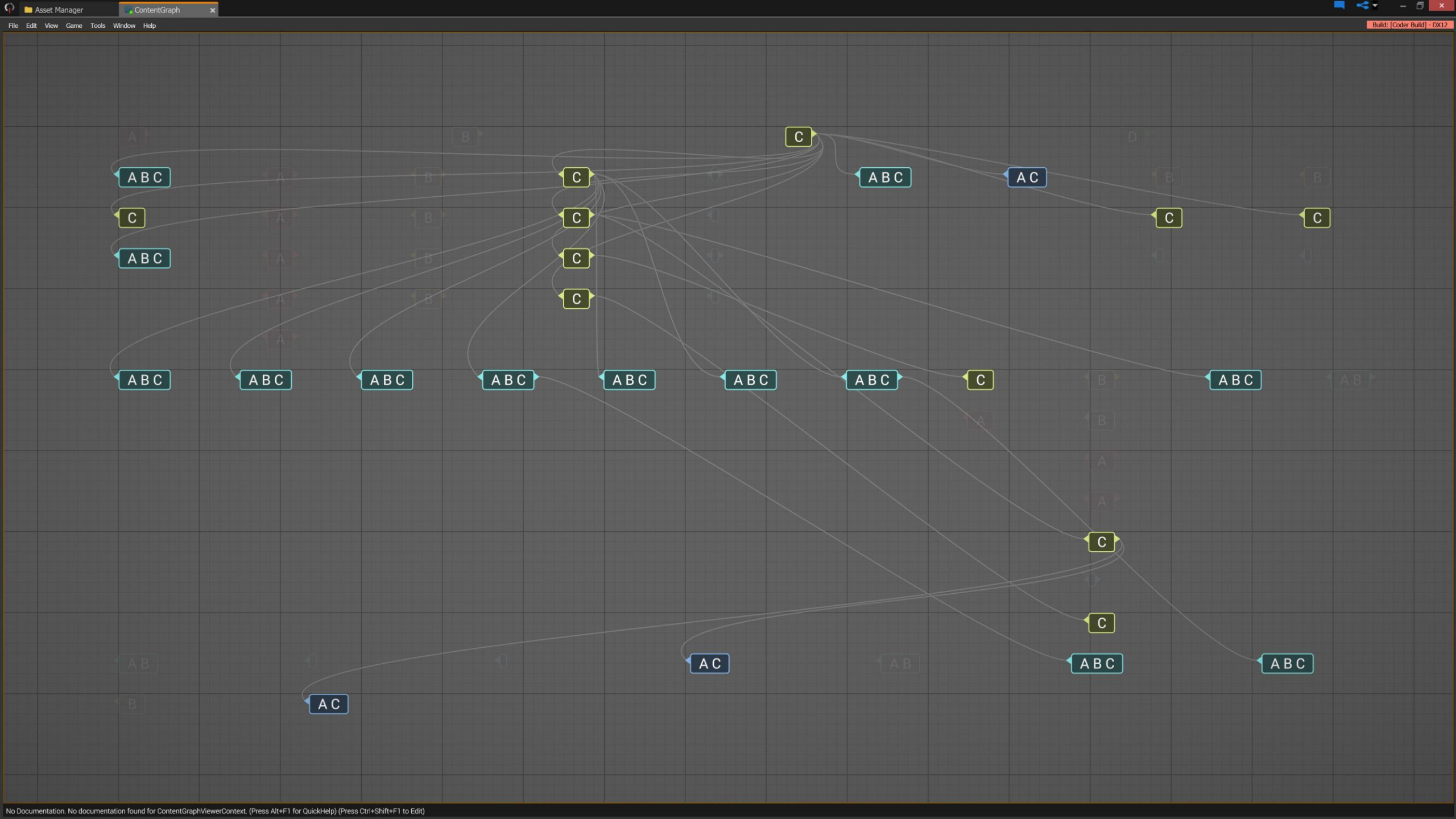
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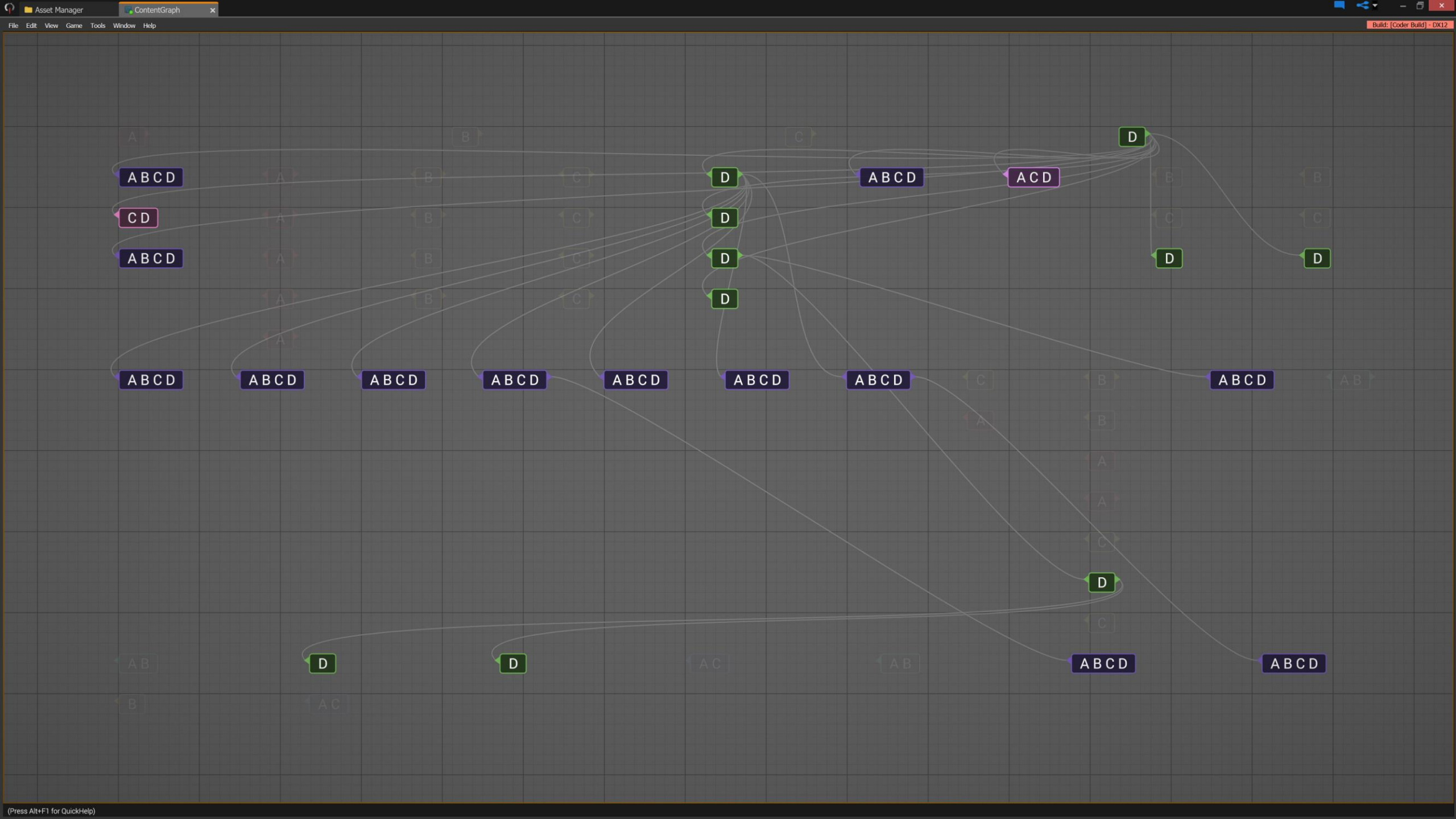
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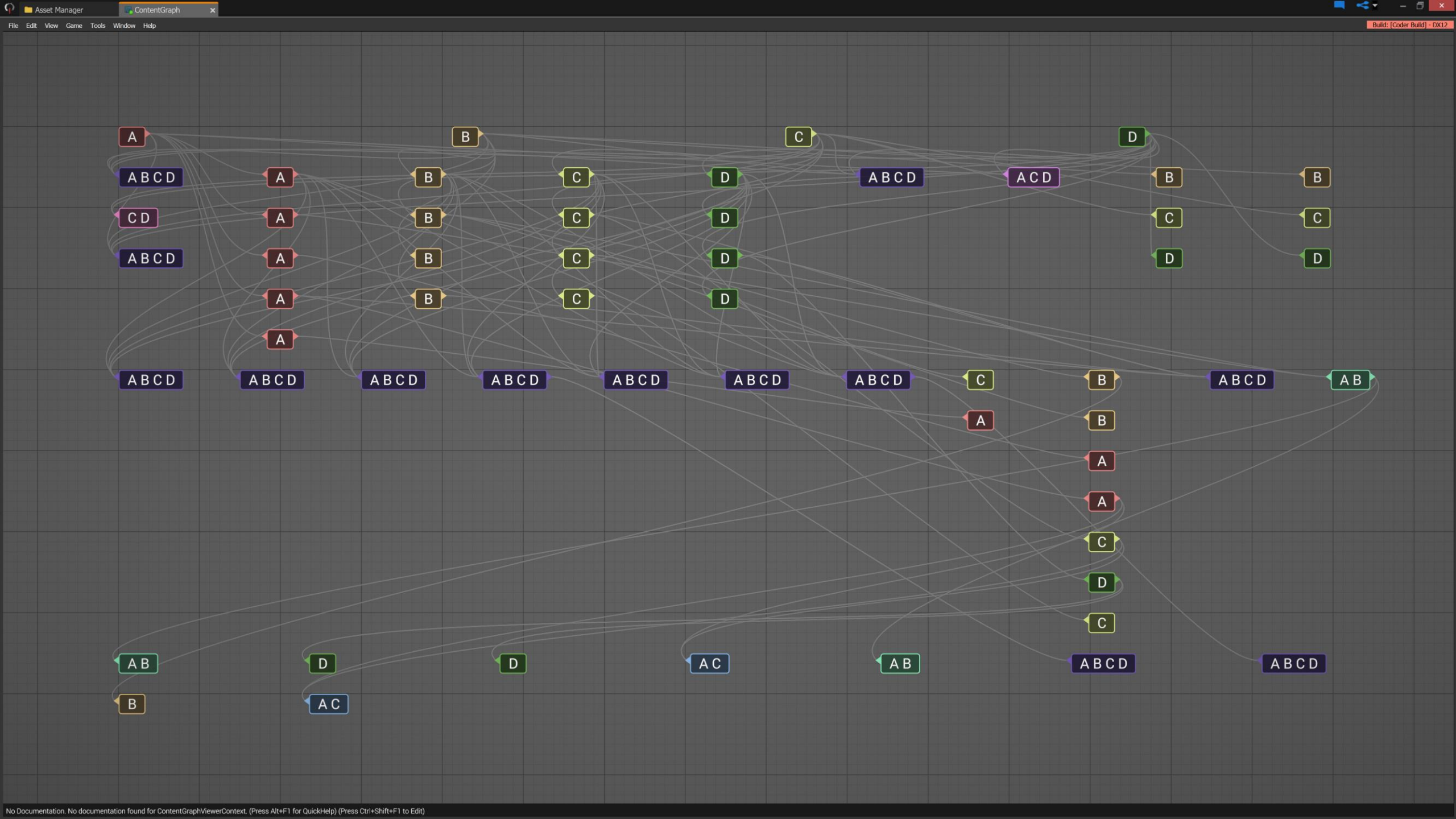
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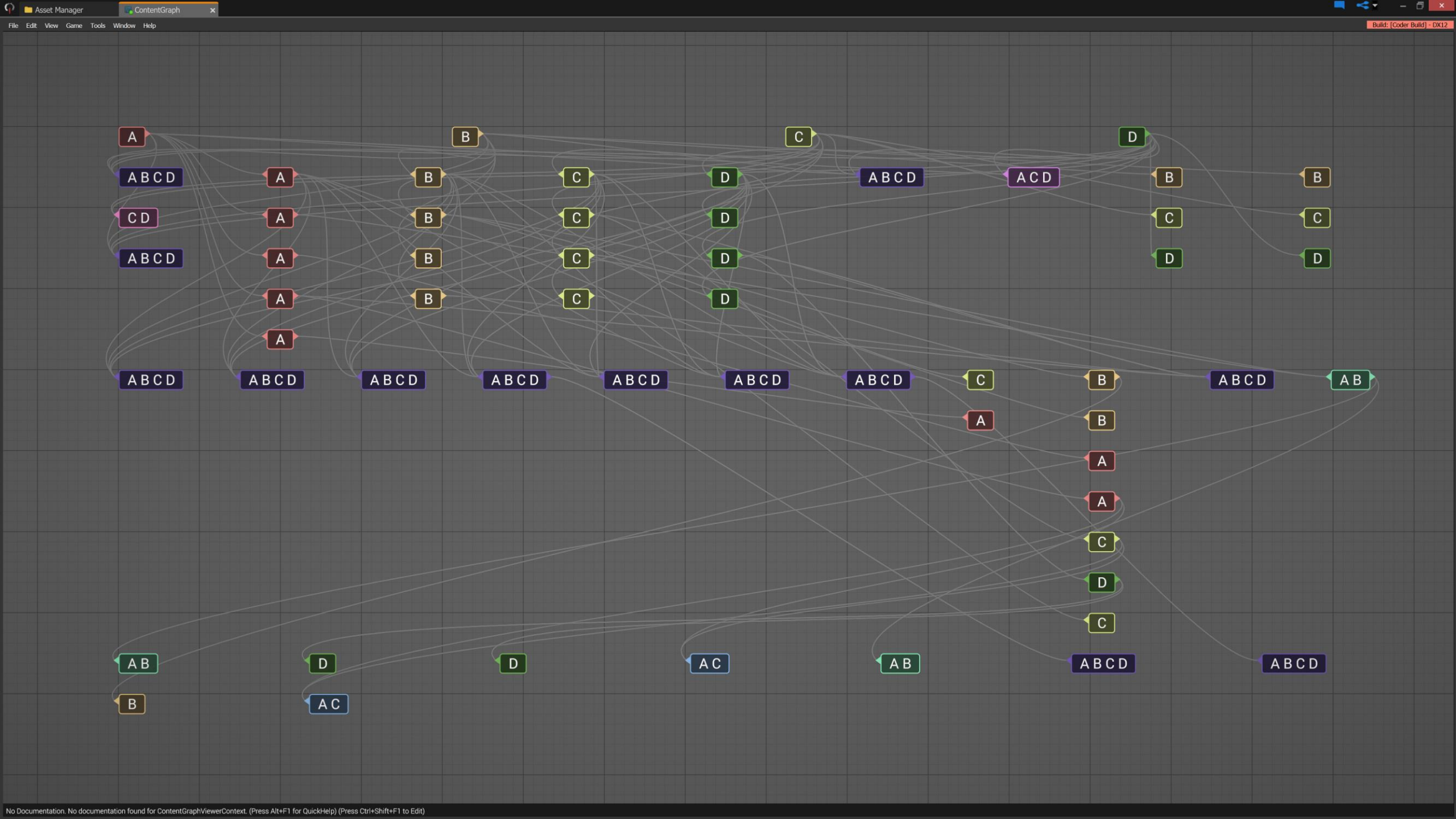
GROUP GRAPH

For each unique combination of identifiers:

- **Create a group node** to represent it
- **Add objects** with that set of identifiers
- **Create links** between groups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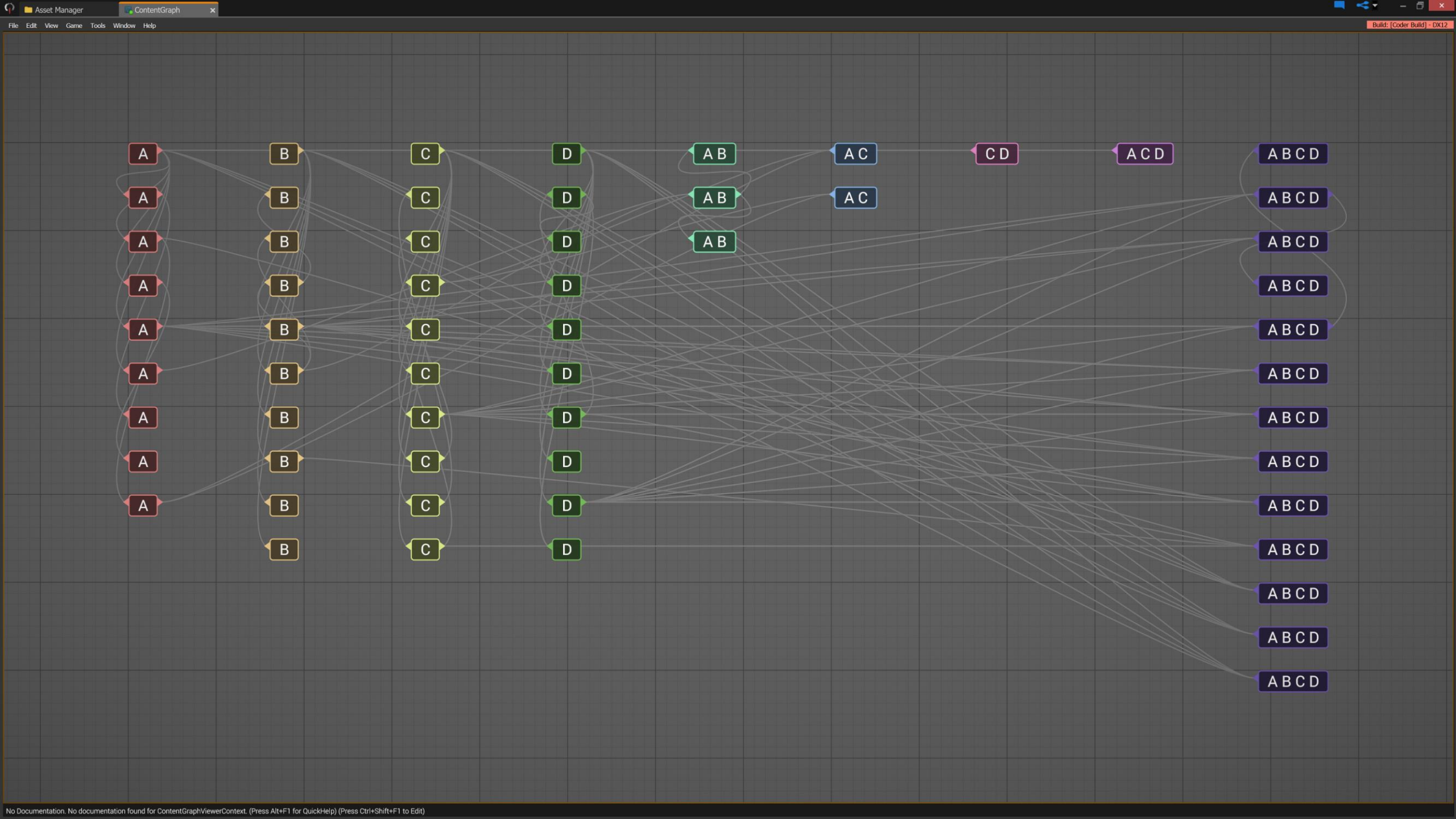
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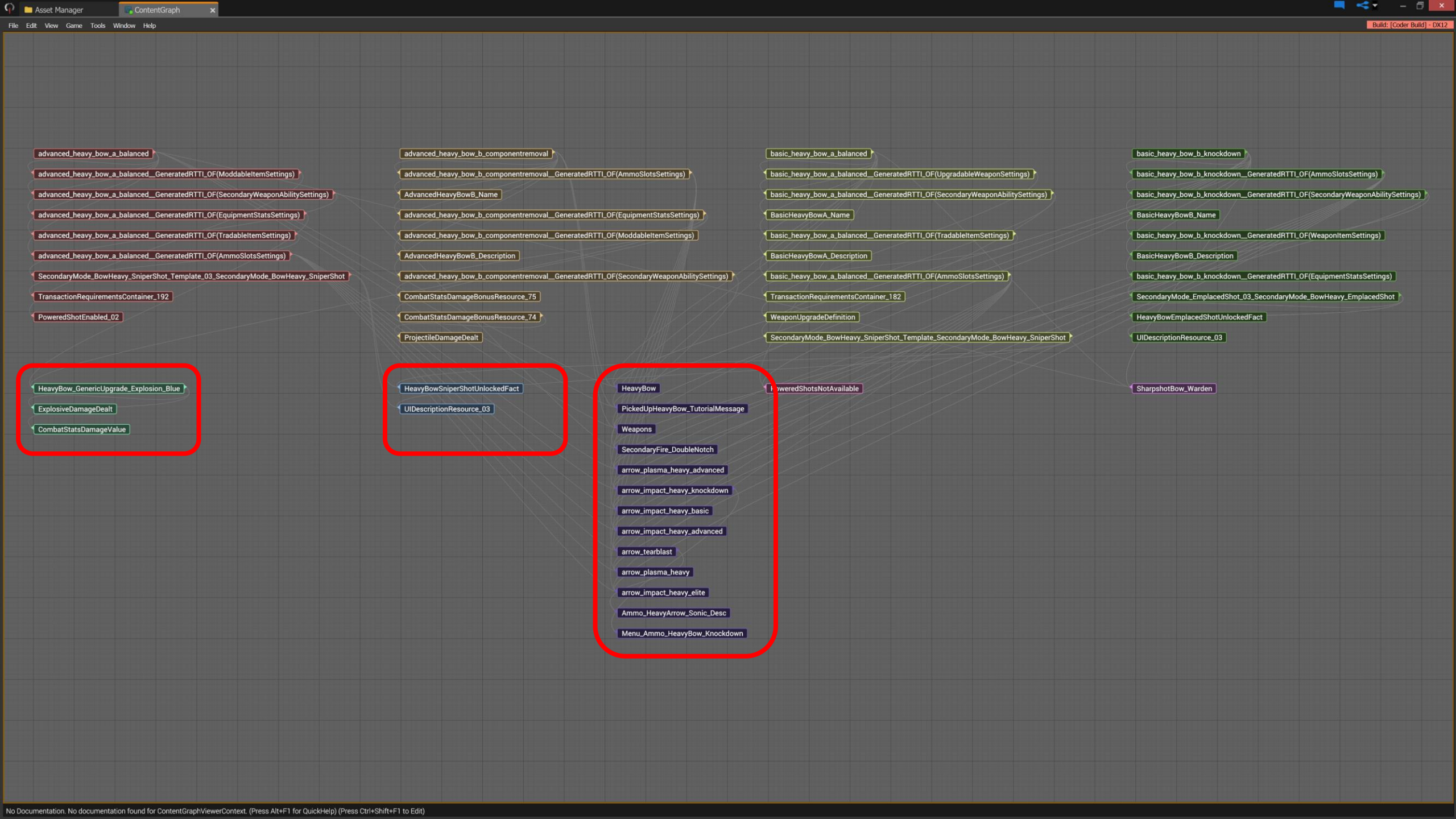
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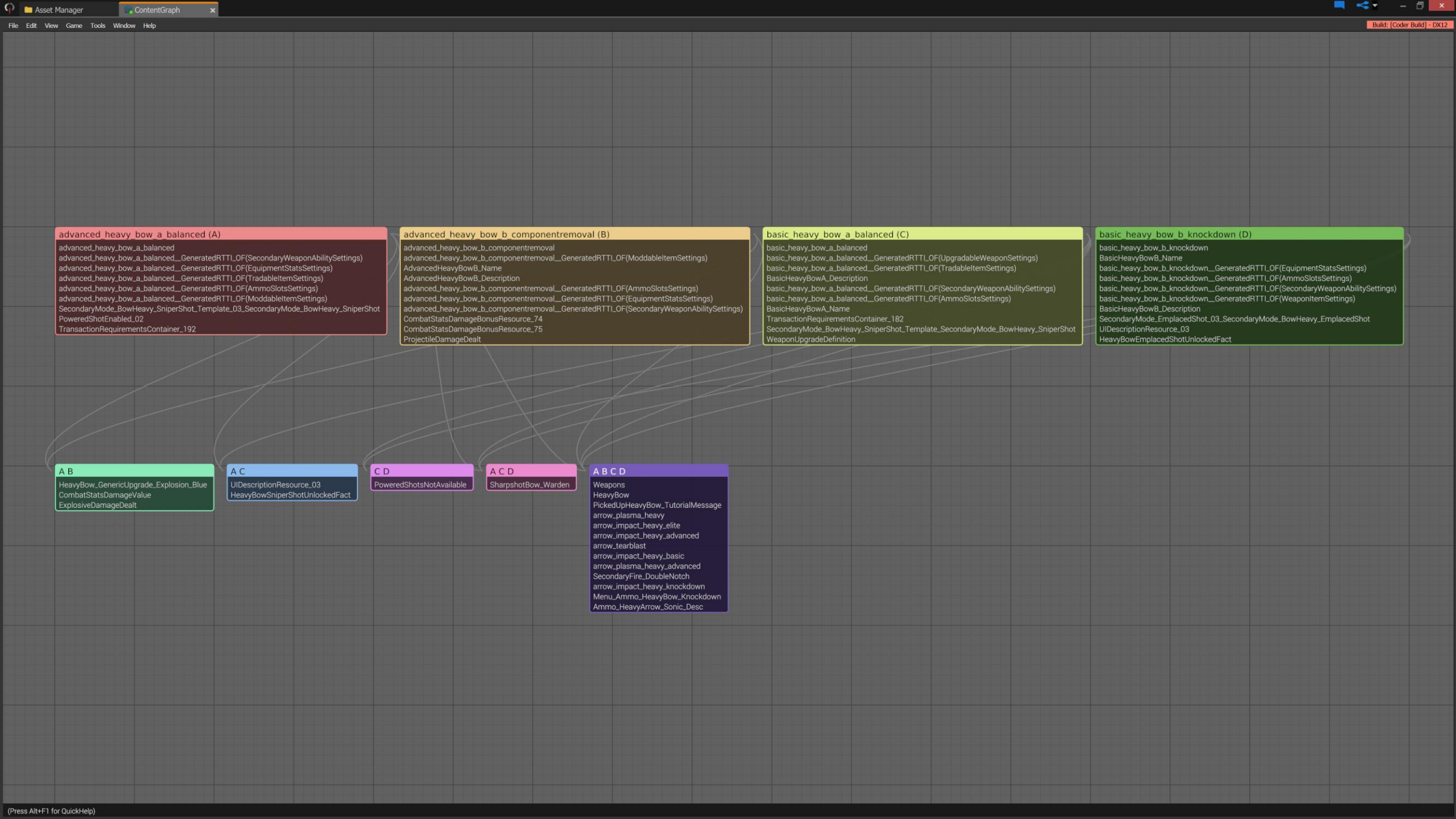
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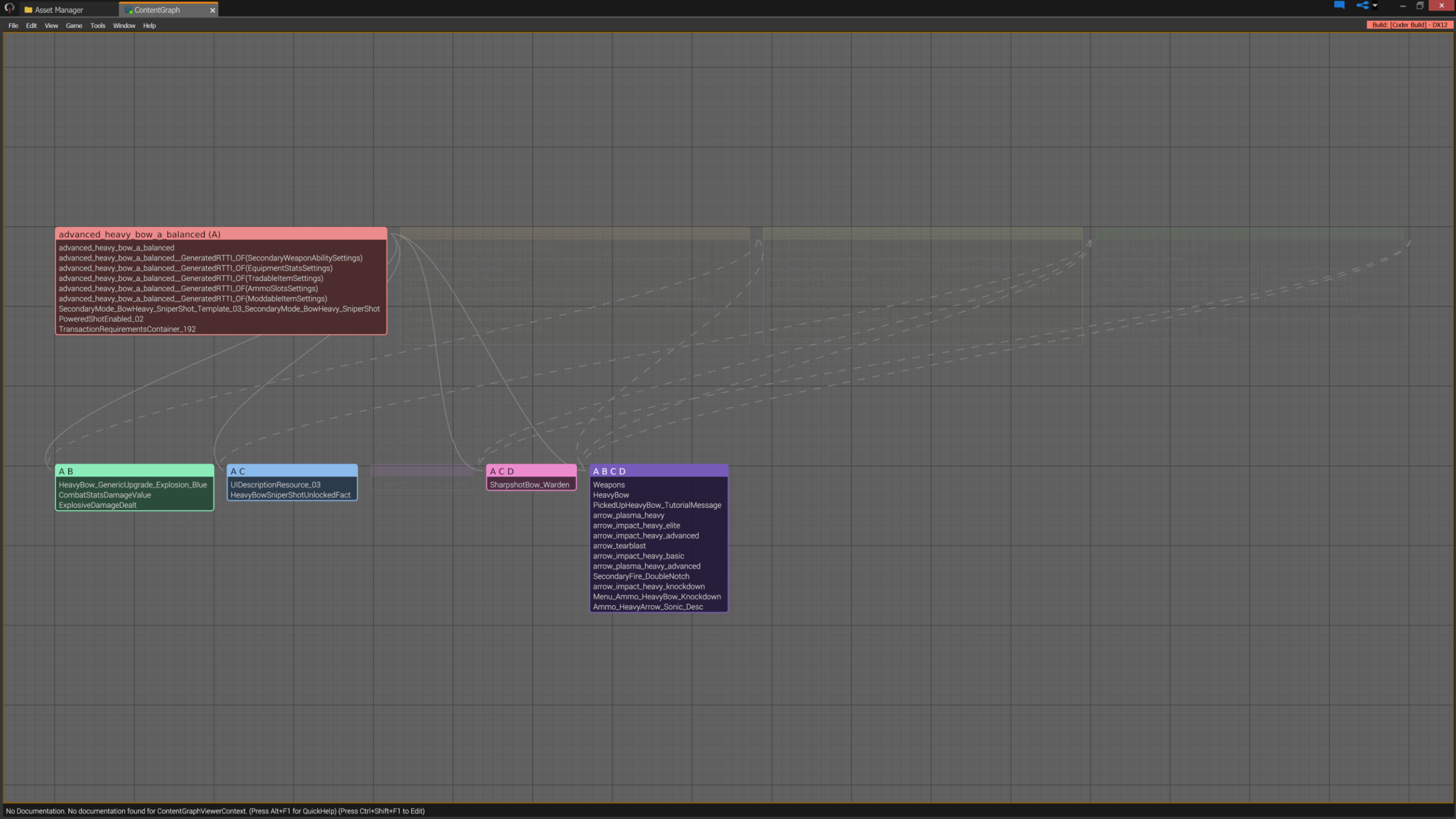
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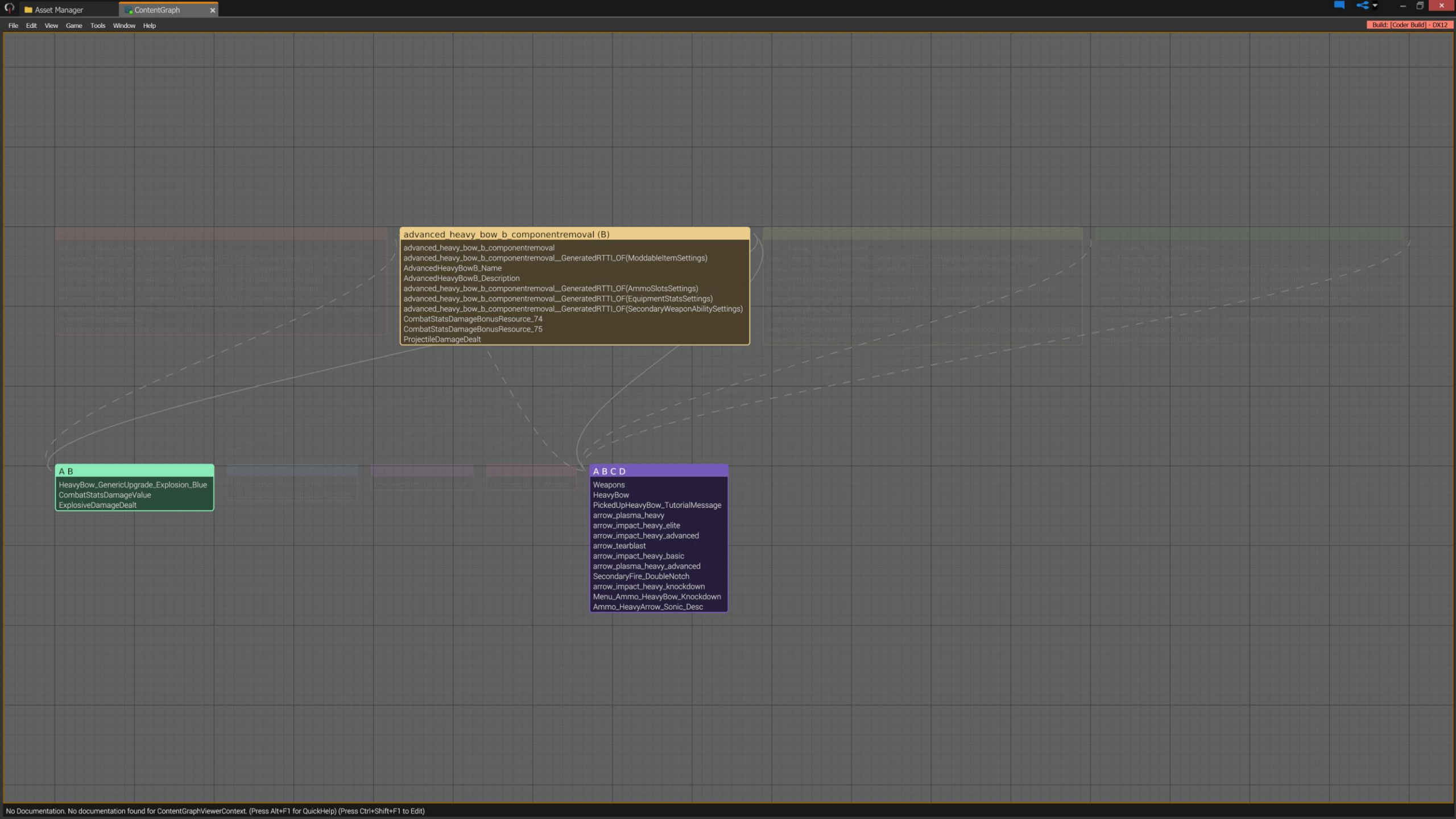
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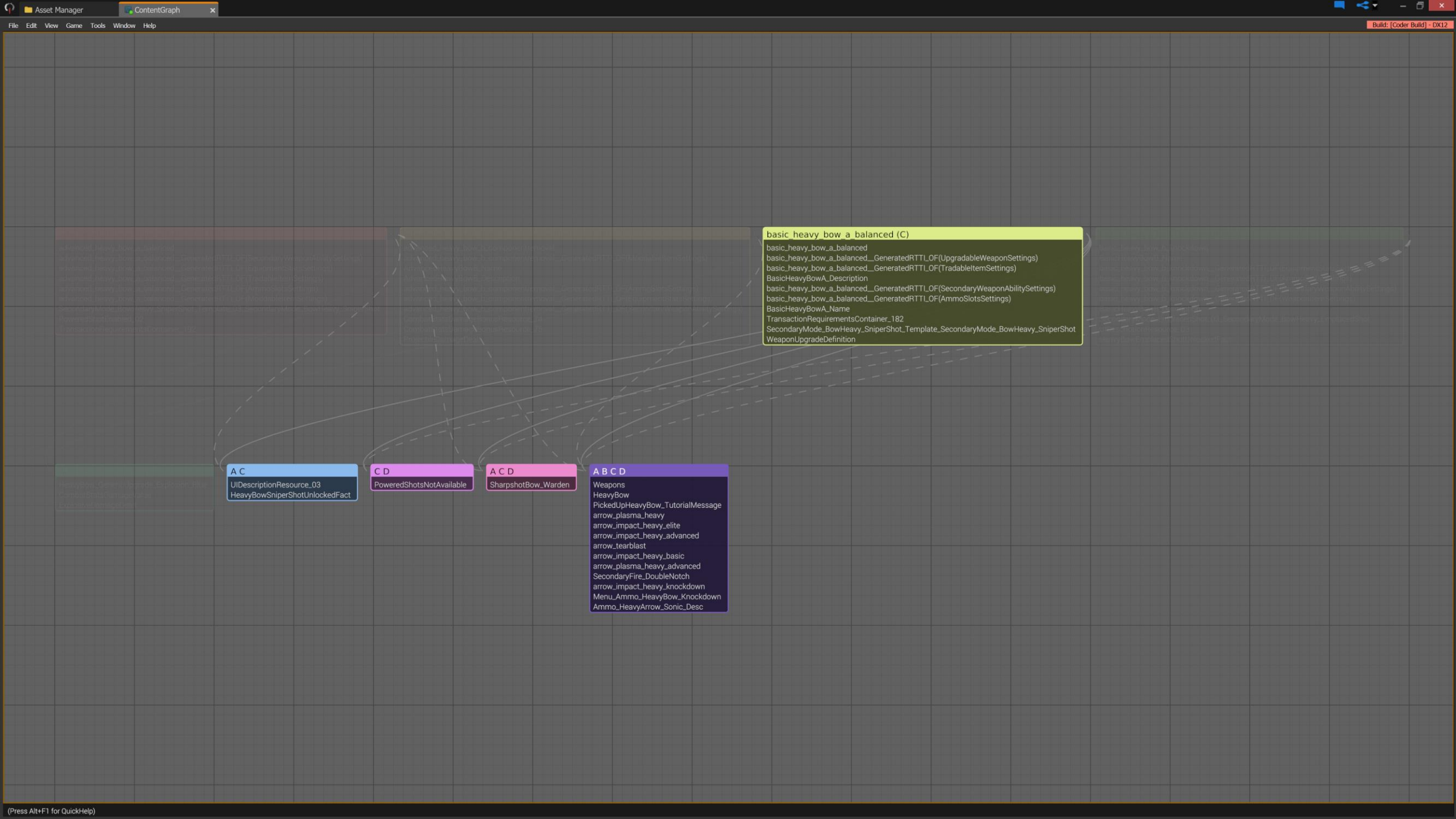
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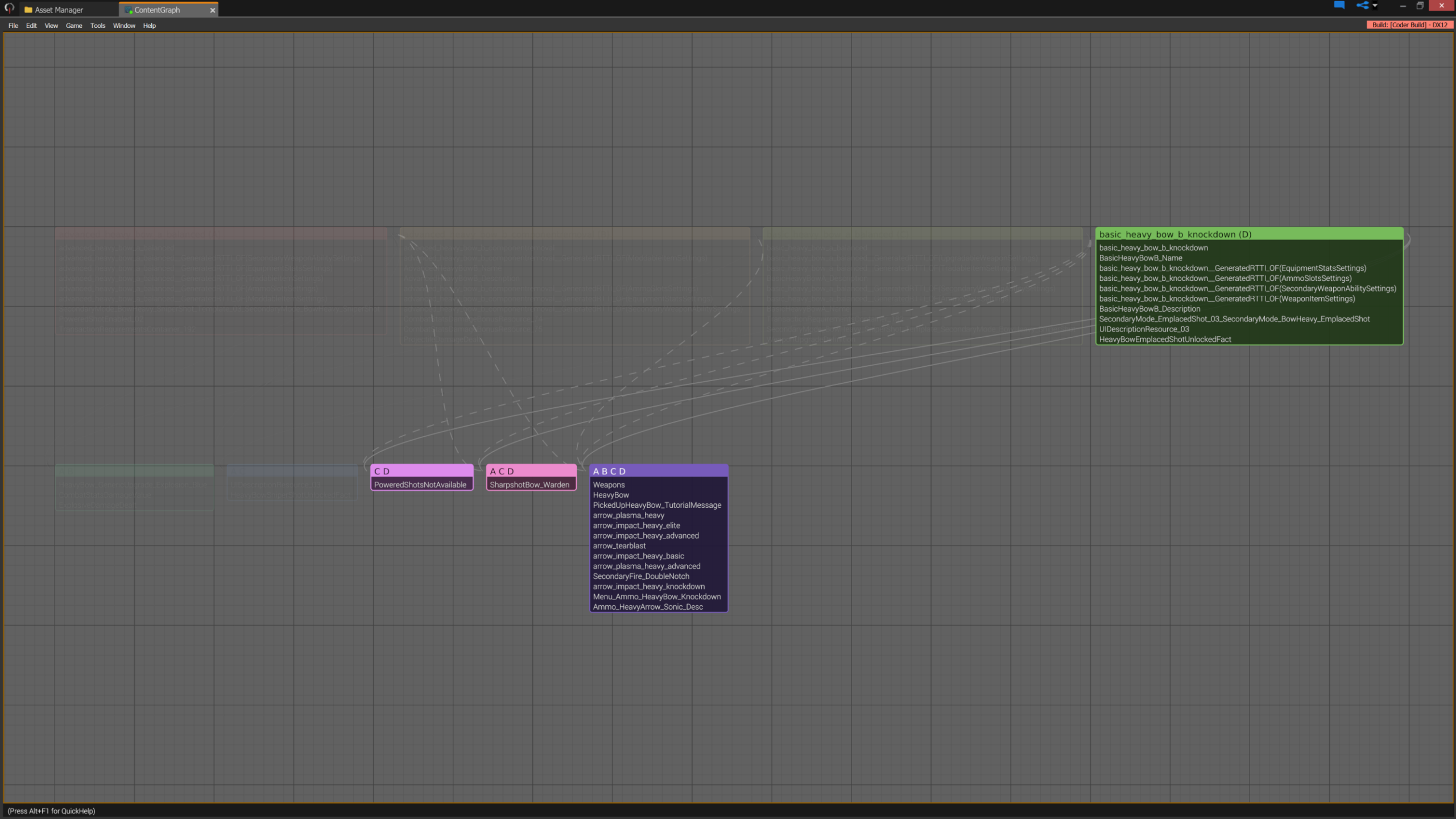
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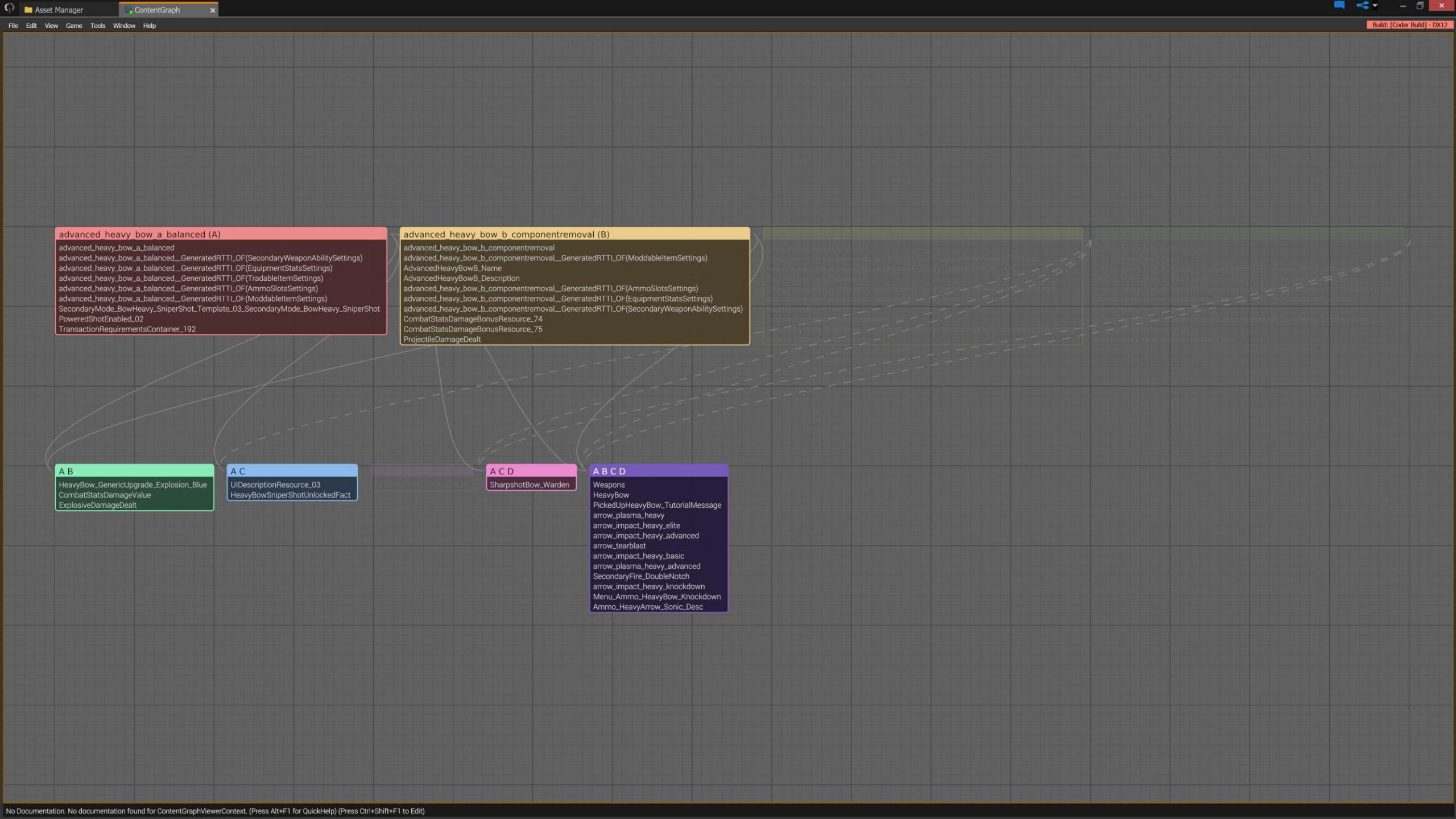
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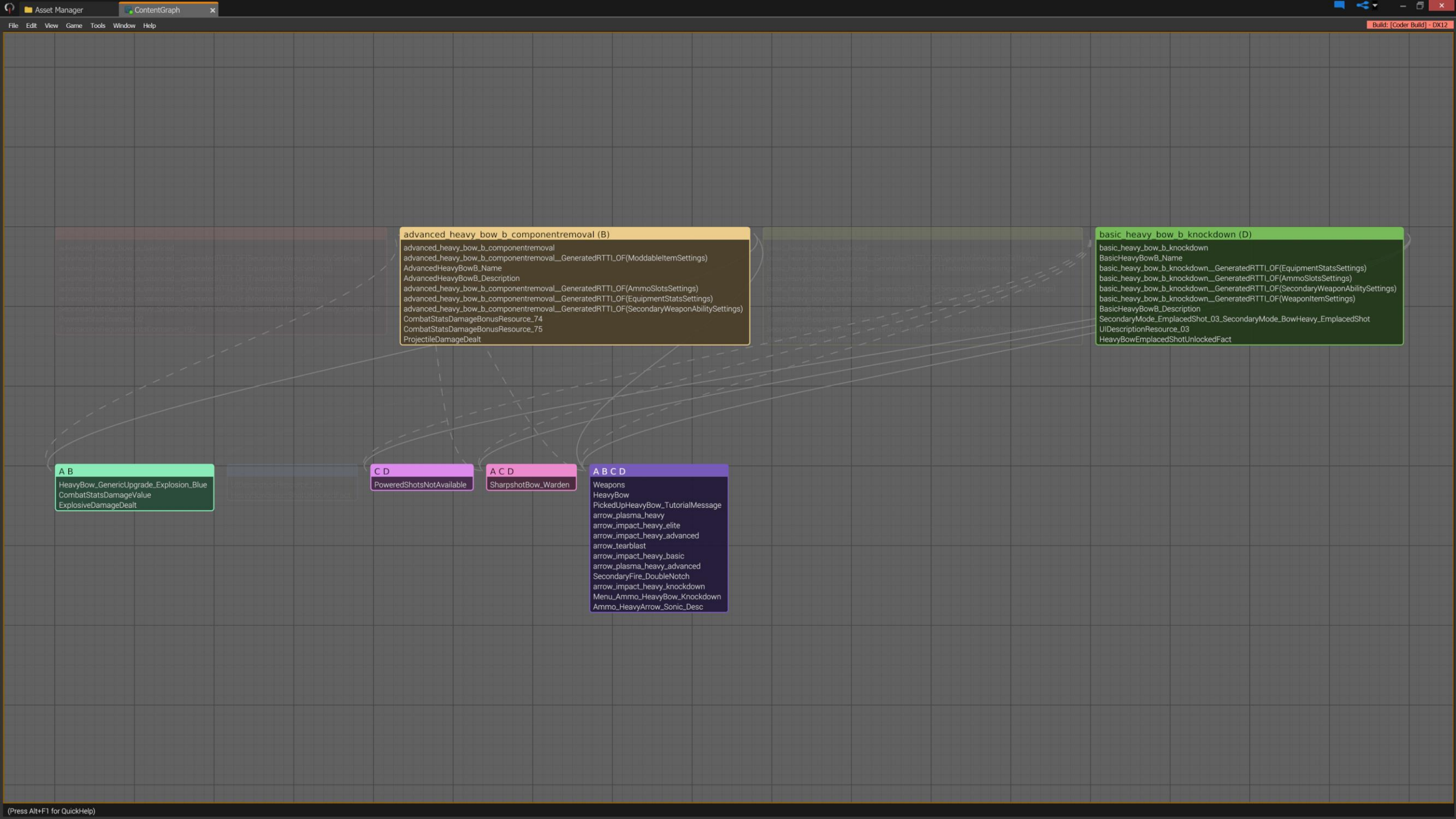
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GROUP GRAPH PROPERTIES

This group graph has some very interesting properties:

- Each root object can be **loaded as a unique set of groups**
- This set will contain **all required objects**
- It contains **no extraneous objects**
- The group **graph is acyclic**
- This is the **smallest object grouping** with these properties

FORBIDDEN WEST CONTENT SCALE

- **600,000** files
- **17 million** objects
- **60 million** links
- **9 million** objects after pruning
- **31,019** root objects
- **85,739** groups

SAVINGS

Group count is **14%** of the original file count

Explicit bookkeeping for 1% of the total object count

No unused objcts saves **300 MiB** runtime memory

For us, that’s more than **10%** memory savings

Unused and debug object stripping saves **30 GiB** content

DEDUPLICATION

Using the graph, we can perform **de-duplication**

- **Content hashes** for each object
- Find **sets of duplicates** in the graph
- **Select single instance** from each set
- **Rewrite links** to the other instances
- Saved **20 GiB** in duplicate shaders and textures

PERFORMANCE

Metadata gathering cost most expensive

Suitable for **parallel processing**

Runs **under a minute** for entire content graph

On regular developer machines

USE DURING DEVELOPMENT

Original implementation **for shipping only**

Algorithm could not run incrementally

File-based streaming still used **during development**

Memory differences problematic at end of development

Converting entire graph for packaging **very time consuming**

Started incremental version after shipping

DEVELOPMENT VERSION

New development system is faster

Algorithm phase is very fast

No packing of data required

Cache, share and re-use metadata

Now we **get rid of the old system!**

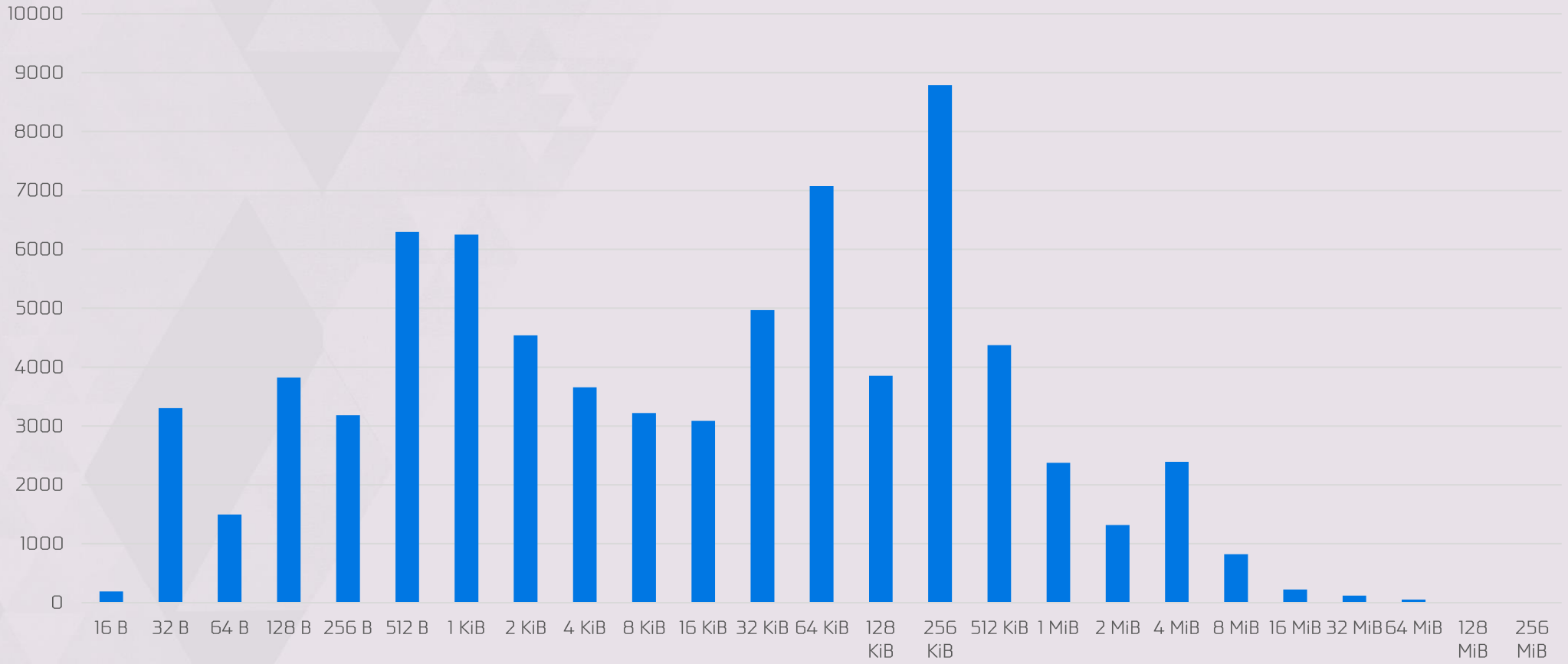
PACKAGING

PACKAGING

The **simplest form** of packaging is to:

- Write each **group as a file**
- Write metadata to **identify root groups**
- Produce metadata for the **group graph**

GROUP COUNT PER SIZE CLASS



IMPROVING READ PERFORMANCE

Poor read performance on many small files

- We opted to writing **successive groups to ~2GiB files**
- These files were **opened on startup and kept open**
- Metadata for **file index and offset** of each group
- **Smart group sorting** allows for **coalescing read operations**

GROUP LAYOUT

The **order of groups** determines **read performance**

- **Player traversal** is **indeterminate**
- Group ordering is generally **undecidable**
- M**any orderings** have **equivalent value**
- There is **no single optimal layout**
- Many **alternative strategies** can be devised

DISK LAYOUT OPTIMIZATION

We worked on a number of **promising optimizations**

- **Merging small groups** into always loaded groups
- **Making a read cache** for the smallest groups
- **Duplicating groups** across the disk

Read performance was more than sufficient without them

Group sorting was key to performance

MAKING DEMOS

Determine which **root objects** you want

Levels, entities, inventory items, costumes

Determine **group graphs from root groups**

Produce **metadata for those groups** only

Extend **high-level systems to check metadata**

Game will **only present what's available**

ON-DEMAND DISTRIBUTION

Store **content identifier** of each group in the metadata

Store root sets in metadata

Determine what the player needs

Find all groups linked from **required roots**

Download missing groups while pruning old groups

Keep **installed size under control**

AUTOMATIC UPDATES

Ensure you download the **latest metadata on startup**.

Remove downloaded groups with **unknown hashes**.

Download missing groups using **new metadata**.

Always **have the content you need** automatically

CAVEATS

There are some things you need to have in place:

- You need **object metadata** to **construct the graph**
- The **link graph must be complete**, no implicit links
- Your **objects must be relocatable** to allow group writing
- **Links must be rewritable,** especially for deduplication

MORE INFORMATION

- Object Streaming system
- Production version with incremental packaging
- Packaging implementation
- Virtual packaging
- Patching strategies
- GlobalStore and data pipeline

IN CONCLUSION

- **Generalized approach** to packaging
- Algorithm delivers **strong guarantees**
- System is **fully automated**
- Applicable for **many scenarios**
- Hopefully **inspires** you
- **Take this further** with us

WE ARE HIRING!

Programming / Central Team

PRINCIPAL TOOLS PROGRAMMER

Posted: 2 days ago

Programming / Central Team

SENIOR TOOLS PROGRAMMER

Posted: 2 days ago