Appendix

Note on reproduced prompts and input texts:
Several sections in this Appendix reproduce the actual natural language prompts, protocol descriptions, and constraint inputs used in the experiments or benchmark runs. These texts are shown as input records for reproducibility and are therefore retained largely verbatim, including minor typographical errors, inconsistent wording, and formatting artefacts present in the original inputs, such as “wel” or other spelling inconsistencies. These reproduced input texts should be distinguished from the corrected experimental descriptions in the main manuscript.

Benchmark against off-the-shelf LLM prompting and repeatability

Methods

To quantitatively compare Labware-Layout Planner (LLP) with off-the-shelf LLM prompting and to assess behavior under repeated identical inputs, we performed a controlled benchmark on the colored-water OT-2 task used in this study (**Figure 3**). The evaluation focused on layout generation only and did not include OT-2 code generation. Two conditions were tested. In the “Vanilla” LLM condition, an off-the-shelf LLM was prompted to output one OT-2 deck-layout JSON directly. In the LLP condition, the same backend LLM was used within the full three-stage pipeline of Labware-Extractor, Position-Planner, and Constraint-Validator. Both conditions were given the same task information, including the process flow, the available labware list, OT-2 deck numbering, canonical naming requirements, the pipette-compatible tip-rack requirement, and the explicit constraint that Color A water and Color B water must not be adjacent within the 8-neighbour deck grid. Two backend LLMs (GPT-4o and GPT-5.4) were used in this benchmark. Each model–condition combination was evaluated over 50 independent runs.These two models were selected to test whether the value of LLP depends on the capability of the underlying LLM by comparing an earlier model with a more recent, stronger model. Outputs were scored at the layout level using predefined checks for slot range (1–11), absence of duplicate slot assignments, satisfaction of the Color A/Color B non-adjacency constraint, use of canonical labware names, and use of a P300-compatible tip rack when a tip rack was included. To characterize repeatability beyond pass/fail rates, we additionally counted the number of unique constraint-satisfying layouts observed among successful runs under identical inputs. For the LLP condition, runs that failed before layout generation, such as repeated JSON parsing failure in the Labware-Extractor stage, were counted separately as pipeline failures.

Results

To evaluate the current implementation against off-the-shelf LLM prompting, we benchmarked GPT-4o and GPT-5.4 in both a Vanilla LLM baseline condition and an LLP condition on the manuscript-aligned colored-water OT-2 task, using matched task constants and 50 repeated identical-input runs per model-method setting (**Table S1**). Under the predefined layout evaluation criteria, GPT-4o in the Vanilla LLM condition produced constraint-satisfying layouts in 26/50 runs (52%), whereas GPT-4o in the LLP condition produced constraint-satisfying layouts in 34/50 runs (68%). All 24 non-passing GPT-4o

Vanilla LLM runs violated the explicit non-adjacency rule between Color A water and Color B water. By contrast, the 16 non-passing GPT-4o LLP runs failed upstream at the Labware-Extractor stage because a parseable structured output was not obtained; among the 34 GPT-4o LLP runs that reached the solver, all 34 satisfied the evaluated layout constraints. With GPT-5.4, both the Vanilla LLM and LLP conditions produced constraint-satisfying layouts in 50/50 runs for this task. Despite identical success rates, differences in repeatability at the layout level remained apparent:among these successful GPT-5.4 runs, the number of unique constraint-satisfying layouts was 11 for Vanilla and 2 for LLP. Overall, these results suggest that LLP improves constraint satisfaction with weaker backends (GPT-4o: 52% for Vanilla vs. 68% for LLP), while with stronger backends that already achieve full constraint satisfaction (GPT-5.4: 100% in both conditions), LLP substantially reduces output variability under identical inputs (11 vs. 2 unique layouts).

Table S1. Controlled benchmark comparing off-the-shelf LLM prompting (“Vanilla”) and Labware-Layout Planner (LLP) on the manuscript-aligned colored-water OT-2 task under repeated identical inputs.
Both conditions were evaluated under matched task constants, including the process flow, available labware list, OT-2 deck numbering, canonical naming requirements, pipette-compatible tip-rack requirement, and the explicit non-adjacency constraint between Color A water and Color B water. Values are from 50 independent runs per model-method setting. “Unique layouts” indicates the number of distinct constraint-satisfying layouts observed among successful runs under identical inputs. “Pipeline failures” indicate runs that did not reach layout evaluation because the LLP pipeline failed upstream during structured extraction.

Task	Backend	LLM Method	Constraint-satisfying layouts (n/50)	Constraint-satisfying layouts (%)	Unique layouts (n)	Pipeline failures (n)
Colored water	GPT-4o	Vanilla	26/50	52	14	N/A
Colored water	GPT-4o	LLP	34/50	68	17	16
Colored water	GPT-5.4	Vanilla	50/50	100	11	N/A
Colored water	GPT-5.4	LLP	50/50	100	2	0

Software Information

Python 3.12
OpenAI o1-preview
OpenAI GPT-4o and GPT-5.4 for off-the-shelf LLM comparison

Available Labware List (ID and Name)

1. 1.5_ml_tube
2. 2.0_ml_tube
3. 15_ml_tube
4. corning_96_wellplate_360ul_flat
5. corning_24_wellplate_3.4ml_flat

6. corning_6_wellplate_16.8ml_flat
7. opentrons_96_tiprack_1000ul
8. opentrons_96_tiprack_300ul
9. opentrons_96_tiprack_20ul
10. opentrons_96_tiprack_10ul
11. nest_12_reservoir_15ml
12. opentrons_10_tuberack_falcon_4x50ml_6x15ml_conical
13. opentrons_24_tuberack_eppendorf_1.5ml_safelock_snapcap
14. opentrons_24_tuberack_eppendorf_2ml_safelock_snapcap

Labware extraction prompt

Overview
You are tasked with extracting specific details from a text describing a scientific experiment. Focus solely on the labware used in the experiment. Use labwares from the available labware list below.

Your Task
Read the given experiment description and extract the following information in JSON format:

1. **Labware Name:** Identify each piece of **labware**, mentioned, identical name. If there are identical laboratory instruments, name them so that they can be distinguished from each other.
2. **Labware Quantity:** Note how much of the labware is used, if mentioned.
3. **Initial Content:** If the labware is a tube, plate, or dish and contains something at the start, describe the content. If it's empty or the content is not specified, leave this field blank.
4. **Labware ID and Name:** Provide an ID and a standardized name for each labware item. Use the available labware list below to match the labware with the correct ID and name. If the labware is not on the list, leave the ID field blank.

Available Labware List (ID and Name)
1. 1.5_ml_tube
2. 2.0_ml_tube
3. 15_ml_tube
4. corning_96_wellplate_360ul_flat
5. corning_24_wellplate_3.4ml_flat
6. corning_6_wellplate_16.8ml_flat
7. opentrons_96_tiprack_1000ul
8. opentrons_96_tiprack_300ul
9. opentrons_96_tiprack_20ul
10. opentrons_96_tiprack_10ul
11. nest_12_reservoir_15ml
12. opentrons_10_tuberack_falcon_4x50ml_6x15ml_conical
13. opentrons_24_tuberack_eppendorf_1.5ml_safelock_snapcap
14. opentrons_24_tuberack_eppendorf_2ml_safelock_snapcap

Guidelines
- For labware with specific contents, list the content name in the "init_content" field. Leave it blank ("init_content": "") if no content is specified.
- Focus on identifying the labware, not the substances it contains. The labware's name should not be confused with the content it holds.
- Assume no sample is created spontaneously; try to infer the origin of all substances as best as you can.
- If a labware's initial content is mixed or not uniform, list it as separate entries to clarify the distinction.
- Clearly indicate which items are present on the experimental bench at the beginning. Do not include substances that appear as a result of the experiment in the "INITIAL CONTENT".

Example
Given Text
Add 100 uL of sample from 1.5 ml tube to 96 well plate.
Transfer 10 ml medium to 15 ml tube.
Add 300 µl of the medium from 15 ml tube to 96 well plate.

Correct Output Format
```json
[
  {"name": "1.5 ml tube sample", "quantity": 1.5, "unit": "ml", "init_content": "sample", "labware": {"id": 1, "name": "1.5_ml_tube"}},
  {"name": "96 well plate medium", "quantity": 1, "unit": "ml", "init_content": "medium", "labware": {"id": 2, "name": "corning_96_wellplate_360ul_flat"}},
  {"name": "15 ml tube", "quantity": 0, "unit": "", "init_content": "", "labware": {"id": 3, "name": "15_ml_tube"}}
]
```

Incorrect Output Format (NG)
```
[
  {"name": "sample", "quantity": 100, "unit": "uL", "init_content": ""},
  {"name": "medium", "quantity": 10, "unit": "ml", "init_content": ""}
]
```

Note: In the incorrect example, the focus is wrongly placed on the contents rather than the labware itself, which is not what is asked for.
Do not directly name the content like {"name":"sample", ...}

Process flow
```
```

{__process_flow_text__}
```
```

Example object list

[
{"name": "1.5 ml tube sample", "quantity": 1.5, "unit": "ml", "init_content": "sample", "labware": {"id": 1, "name": "1.5_ml_tube"}},
{"name": "96 well plate medium", "quantity": 1, "unit": "ml", "init_content": "medium", "labware": {"id": 2, "name": "corning_96_wellplate_360ul_flat"}},
{"name": "15 ml tube", "quantity": 0, "unit": "", "init_content": "", "labware": {"id": 3, "name": "15_ml_tube"}}
]

Experimental protocol (mixing of the colored water)

Constraints for prompt.
P300_SINGLE_GEN2 is on the LEFT in OT-2.

Process flow
Preparation: Prepare each of two types of colored water (Color A, 'Color A water' and Color B, 'Color A water'). The colored water is diluted with water using food coloring.
Note: The A color water and B color water have been prepared in advance and is stored in different 6-well plates.
Preparation of the 96 well plate: Set an empty 96 well plate on the experimental bench.
Mixing of the colored water:
Using a micropipette, add 10 µl of Color A water and 0 µl of Color B water to the first well. Then, by decreasing the amount of Color A water by 1 µl and increasing the amount of Color B water by 1 µl for each well, add 9 µl of Color A water and 1 µl of Color B water for the next well and so on.
Continue...
Finally, add 0 µl of Color A water and 10 µl of Color B water to the last wel (10-th well).

Absolute restriction (mixing of the colored water)

[]

Relative restriction (mixing of the colored water)

[
{
"restriction_category": "init_content",
"labware_id": "Color A water",
"restriction_type": "adjacent",
"adjacent_type": "grid",
"neighbour_types": ["Color B water"],
"description": "Not adjacent to 8 surrounding squares"
},

{

```
    "restriction_category": "name",
    "labware_id": "Color A water",
    "restriction_type": "adjacent",
    "adjacent_type": "around",
    "neighbour_types": ["Color B water"],
    "description": "Not adjacent to 8 surrounding squares"
  }
]
```


Experimental protocol (PCR mix preparation experiment)

Prepare samples for measurement with the QuantStudio 6 Pro.
There is 1 sample, and it will be tested with 3 primers × duplicate (3).
For the NTC, prepare 3 primers × duplicate (3).
Additionally, prepare one template-only sample without primers × duplicate (3).
Input: Containers for reagents are tubes or plates

1 sample DNAs	300 µL
water	300 µL
10 µM primer_F	10 µL each
10 µM primer_R	10 µL each
PCR MIX	2000 µL
96-well PCR plate	1 plate

Other necessary tubes or plates for liquid mixing

Output
One 96-well PCR plate containing mixed solutions of sample DNA, primers, and PCR MIX.

Procedure
Dispense 137.6 µL of PCR MIX into each of 3 tubes.
Add 3.2 µL of 10 µM primer_F1–3 to the tubes containing PCR MIX.
Add 3.2 µL of 10 µM primer_R1–3 to the tubes containing PCR MIX.
Mix PCR MIX and primers by pipetting.
Dispense 86 µL of PCR MIX into a tube for the template-only condition.
Add 4 µL of water to the PCR MIX for the template-only condition.
Mix PCR MIX and water for the template-only condition by pipetting.
Apply 5 µL each of sample DNA or water to the reaction plate.
    (Fill in the columns of the plate map below.)
Apply 10 µL each of the PCR MIX and primer mixture to the reaction plate.
    (Fill in the rows of the plate map below.)

Plate map
81 wells used
S_n = sample_n (this time: one human standard cDNA)
NTC = no template control: water = negative control (set for all primers)
P_m = primer set_m: a pair of forward and reverse primers (3 sets this time)
Also include template-only wells.
OT-2 pipettes
20 µL and 300 µL

Notes
Prepare 10 µM primer_F and 10 µM primer_R together in the same Corning 96 Well Plate 360 µL Flat.

For 1 sample DNAs, water, and other solutions that can be stored in the same container, prepare them together in a plate with an assigned name as much as possible.
Prepare PCR MIX in a 15 mL tube.
As a rule, use 15 mL tubes, 1.5 mL tubes, Corning 96 Well Plate 360 µL Flat, and 96-well PCR plates.

Absolute restriction (PCR mix preparation experiment)

[]

Relative restriction (PCR mix preparation experiment)

[]

Experimental protocol (HEK293A cell passaging experiment)

Purpose
Conduct the Mahoro experiment as part of the FF paper. This experiment documents the natural language version in order to generate an object list and initial configuration from natural language.

Available materials (any number of them)
"labware"
"name"
- "50 ml tube"
- "6-well plate"

"init_content"
- "PBS"
- "medium"
- "trypsin"
- "HEK293A cells"

Plan
Completed Pre-Work (-2 days)
- HEK293A cells have been seeded into one well of a 6-well plate at a density of 1×10^5 cells per well and cultured in a CO_2 incubator (37°C, 5%).

(Day 0)
- Perform microscopic observation to assess the state of the cells, then carry out the following passage procedures:
  1. Prepare PBS (30 mL in a 50 mL tube), medium (30 mL in a 50 mL tube), and trypsin (30 mL in a 50 mL tube).
  2. Heat the PBS and medium in an aluminum bath at 37°C for 15 minutes.
  3. Remove the 6-well plate from the CO_2 incubator and aspirate the medium from the well containing the cells.
  4. Add 2 mL of PBS.
  5. Aspirate and remove the added PBS.
  6. Add 1.5 mL of trypsin and incubate in the CO_2 incubator (37°C, 5%) for 10 minutes.
  7. Add an additional 1.5 mL of medium to the incubated well and pipette to suspend the cells.

8. In a new 6-well plate, add 2.625 mL of medium to one well.
9. Add 375 µL of the cell suspension prepared in step (7) to the well from step (8) and tilt the plate to mix.
10. Place the plate into the CO_2 incubator (37°C, 5%).

Absolute restriction (HEK293A cell passaging experiment)

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Relative restriction (HEK293A cell passaging experiment)

[]

Labware-Extractor Prompt Example (mixing of the colored water)

```
## Overview
You are tasked with extracting specific details from a text describing a scientific experiment. Focus solely on the labware used in the experiment. Use labwares from the available labware list below.

## Your Task
Read the given experiment description and extract the following information in JSON format:

1. **Labware Name:** Identify each piece of **labware**, mentioned, identical name. If there are identical laboratory instruments, name them so that they can be distinguished from each other.
2. **Labware Quantity:** Note how much of the labware is used, if mentioned.
3. **Initial Content:** If the labware is a tube, plate, or dish and contains something at the start, describe the content. If it's empty or the content is not specified, leave this field blank.
4. **Labware ID and Name:** Provide an ID and a standardized name for each labware item. Use the available labware list below to match the labware with the correct ID and name. If the labware is not on the list, leave the ID field blank.

## Available Labware List (ID and Name)
1. 1.5_ml_tube
2. 2.0_ml_tube
3. 15_ml_tube
4. corning_96_wellplate_360ul_flat
5. corning_24_wellplate_3.4ml_flat
6. corning_6_wellplate_16.8ml_flat
7. opentrons_96_tiprack_1000ul
```

8. opentrons_96_tiprack_300ul
9. opentrons_96_tiprack_20ul
10. opentrons_96_tiprack_10ul
11. nest_12_reservoir_15ml
12. opentrons_10_tuberack_falcon_4x50ml_6x15ml_conical
13. opentrons_24_tuberack_eppendorf_1.5ml_safelock_snapcap
14. opentrons_24_tuberack_eppendorf_2ml_safelock_snapcap

Guidelines
- For labware with specific contents, list the content name in the "init_content" field. Leave it blank ("init_content": "") if no content is specified.
- Focus on identifying the labware, not the substances it contains. The labware's name should not be confused with the content it holds.
- Assume no sample is created spontaneously; try to infer the origin of all substances as best as you can.
- If a labware's initial content is mixed or not uniform, list it as separate entries to clarify the distinction.
- Clearly indicate which items are present on the experimental bench at the beginning. Do not include substances that appear as a result of the experiment in the "INITIAL CONTENT".

Example
Given Text
Add 100 uL of sample from 1.5 ml tube to 96 well plate.
Transfer 10 ml medium to 15 ml tube.
Add 300 µl of the medium from 15 ml tube to 96 well plate.

Correct Output Format
```json
[
  {"name": "1.5 ml tube sample", "quantity": 1.5, "unit": "ml", "init_content": "sample", "labware": {"id": 1, "name": "1.5_ml_tube"}},
  {"name": "96 well plate medium", "quantity": 1, "unit": "ml", "init_content": "medium", "labware": {"id": 2, "name": "corning_96_wellplate_360ul_flat"}},
  {"name": "15 ml tube", "quantity": 0, "unit": "", "init_content": "", "labware": {"id": 3, "name": "15_ml_tube"}}
]

### Incorrect Output Format (NG)
[
  {"name": "sample", "quantity": 100, "unit": "uL", "init_content": ""},
  {"name": "medium", "quantity": 10, "unit": "ml", "init_content": ""}
]
```

Note: In the incorrect example, the focus is wrongly placed on the contents rather than the labware itself, which is not what is asked for.
Do not directly name the content like {"name":"sample", ...}

Process flow
```
{
# Constraints for prompt.
P300_SINGLE_GEN2 is on the LEFT in OT-2.

# Process flow
Preparation: Prepare each of two types of colored water (Color A, 'Color A water' and Color B, 'Color A water'). The colored water is diluted with water using food coloring.
Note: The A color water and B color water have been prepared in advance and is stored in different 6-well plates.
Preparation of the 96 well plate: Set an empty 96 well plate on the experimental bench.
Mixing of the colored water:
Using a micropipette, add 10 µl of Color A water and 0 µl of Color B water to the first well.
Then, by decreasing the amount of Color A water by 1 µl and increasing the amount of Color B water by 1 µl for each well, add 9 µl of Color A water and 1 µl of Color B water for the next well and so on.
Continue...
Finally, add 0 µl of Color A water and 10 µl of Color B water to the last wel (10-th well).
}
```
```

Use these instructions to ensure each labware item is clearly listed with name, quantity, unit, initial content, and matched labware ID/name from the labware list.
```
}
"""