Health-Aware Meal Recommendations using Contextual Multi-Armed Bandits

FCPS Case Study — Group 8

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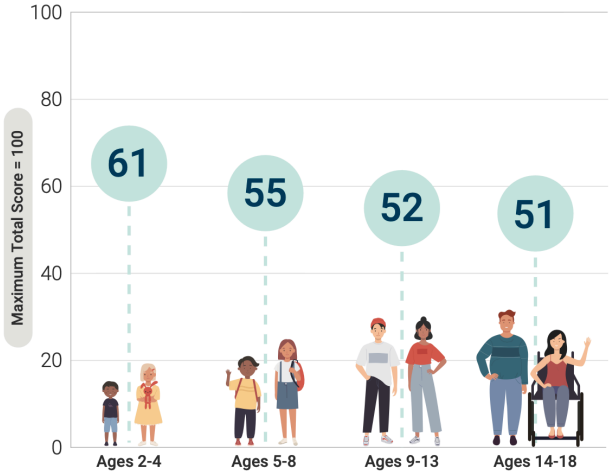
Outline

Eating Trends

Healthy Eating Index Scores Across Childhood and Adolescence



Data Source: Analysis of What We Eat in America, NHANES 2015-2016, ages 2 through 18, day 1 dietary intake, weighted.

Motivation

CHALLENGE

- Students missing nutritional benefits
- Static menus don't adapt to preferences

OUR VISION

- What if every school meal could be both *what kids love to eat* and *what keeps them healthy?*

SOLUTION

- Learn adaptive, data-driven meal recommendations.

Why Reinforcement Learning (RL) and CMAB?

- **Why RL?**
  - Traditional supervised models only predict outcomes from past data.
  - Meal planning, however, is an interactive problem — we choose a menu (action), observe student response (reward), and must adapt future choices.
- **Why CMAB?**
  - Each decision depends on current **context** (school, time, weekday) but not on future states.
  - CMAB provides a simple, efficient RL framework for **context-aware meal recommendations**.

CMAB Framework Overview

- **Context**: school, time_of_day, day_of_week.
- **Action**: meal (`item_id`).
- **Reward**: $r_t = \text{total\_meals\_served} \times (1 + \lambda \times \text{health\_score})$
- Focus: balancing exploration and exploitation.

Sales Dataset (FCPS)

- Includes schools, timestamps, and meal details.
- **Context variables:** school, time, day, seasonality.
- **Action space:** 160+ meal items (arms).

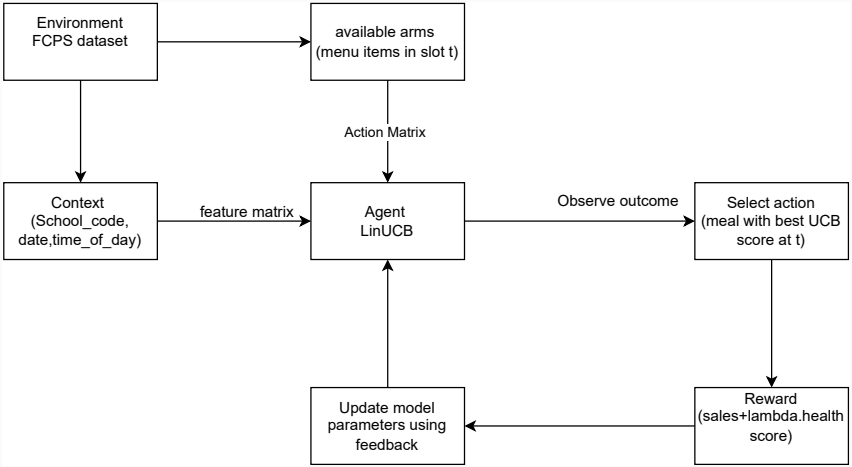
sales

time_of_day	school_code	school_name	date	item	description	total	free_meals	reduced_price_meals	full_price_meals	adults	alac_student	alac_adult	earned_student	earned_adult	earned_alac_student	earned_alac_adult	adj_alac	adj_meal
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1146	CEREAL MEAL	19	3	0	16	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1164	BAGEL W/CREAM CHEESE	6	0	0	6	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1310	ALC BREAKFAST ENTREE	11	0	0	0	0	11	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	151	CEREAL/ NO MILK	13	0	0	0	0	13	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	188	$1.00 WATER 16.9oz	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	600	ALC VEGETABLE/FRUIT	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	717	ALCJUICE 4OZ $.75	44	0	0	0	0	44	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1146	CEREAL MEAL	17	1	0	16	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1234	MANDARIN PARFAIT	2	0	0	2	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1310	ALC BREAKFAST ENTREE	5	0	0	0	0	5	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1406	TURKEY & CHEESE ON BISCUIT	1	0	0	1	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1421	BLUEBERRY BREAD W/ STRING CHEESE	6	0	0	6	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	151	CEREAL/ NO MILK	13	0	0	0	0	13	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	188	$1.00 WATER 16.9oz	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	600	ALC VEGETABLE/FRUIT	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	700	ALC MILK	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	717	ALCJUICE 4OZ $.75	42	0	0	0	0	42	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1146	CEREAL MEAL	19	2	0	17	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1310	ALC BREAKFAST ENTREE	5	0	0	0	0	5	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1406	TURKEY & CHEESE ON BISCUIT	1	0	0	1	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1421	BLUEBERRY BREAD W/ STRING CHEESE	4	0	0	4	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	151	CEREAL/ NO MILK	15	0	0	0	0	15	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	600	ALC VEGETABLE/FRUIT	2	0	0	0	0	2	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	700	ALC MILK	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	717	ALCJUICE 4OZ $.75	48	0	0	0	0	48	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/06/2025	1146	CEREAL MEAL	6	1	0	5	0	0	0	0	0	0	0	0	0

Data Collection Overview

- **Nutrition Data (LINQ Connect API)**
  - Obtained through scraping of the vendor's public API endpoints.
  - Provides nutritional facts for all menu items.
  - Tracks 18 nutrients per item.
  - Coverage includes 160 unique meal items.
- **Sales Data (FCPS Records)**
  - 224,536 transaction records collected.
  - Data from 187 schools across FCPS.
  - Spans over March - May 2025.

LinUCB Flow for FCPS



System Design Overview

Modules

1. `env.py` — Build required FCPS environment such as action matrix,feature matrix etc
2. `model.py` — Implements LinUCB bandit model
3. `main.py` — Trains and evaluates the system
4. `utils.py` — helper function

Data Flow

Dataset $\rightarrow$ Environment $\rightarrow$ Model $\rightarrow$ Results

LinUCB: Upper-Confidence-Bound for Contextual Bandits

- For arm a, at time t with context $x_{t,a} \in \mathbb{R}^d$:

$$p_{t,a} = \theta_a^\top x_{t,a} \; + \; \alpha\sqrt{x_{t,a}^\top A_a^{-1} x_{t,a}}$$

- Balances exploitation (expected reward $\theta_a^\top x_{t,a}$) and exploration (uncertainty term).
- Each arm maintains:
  - $A_a = \sum_{\tau=1}^{t-1} x_{\tau,a} x_{\tau,a}^\top + \lambda I_d$ (regularized covariance matrix)
  - $b_a = \sum_{\tau=1}^{t-1} x_{\tau,a} y_{\tau,a}$ (reward observations)
  - $\theta_a = A_a^{-1} b_a$ (ridge regression solution)

Training & Lifecycle

- `train()`: iteratively selects meals, observes rewards, updates model.
- `action()`: chooses arm maximizing UCB.
- `update()`: applies observed reward to statistics.
- `reset()` & `save()`: manage experiment lifecycle and persistence.

Health Score (NRF9.3 Index)

- **Good Nutrients (Encouraged):** Protein, Dietary Fiber, Vitamin D, Calcium, Iron, Potassium, Vitamin A, Vitamin C.
- **Bad Nutrients (To Limit):** Added Sugars, Saturated Fat, Sodium.
- **Formula:**

$$\text{NRF9.3} = \sum(\%\text{DV}_{\text{good}}) - \sum(\%\text{DV}_{\text{bad}})$$

- **Normalization:** Raw NRF9.3 scores are scaled to a standardized range (0–10) for comparability across meals and school groups.
- **Daily Values (DV):** Adjusted per school level (Elementary, Middle, High School) based on USDA dietary guidelines.
- Enables data-driven evaluation of meal health quality using the NRF9.3 framework.

Features

For a particular date t, we restrict our selection of menu items to only those that were actually served (mask):

$$\mathcal{A}_t \leftarrow \{\text{Cereal}, \text{Apples}, \text{Juice}\}$$

For each available item $a \in \mathcal{A}_t$, we construct feature vectors $\mathbf{x}_{t,a}$ that include nutritional, popularity and school related information:

$$\mathbf{x}_{t,a} = \begin{bmatrix} p \in \mathbb{R} \leftarrow \text{protein grams (one serving)} \\ c \in \mathbb{R} \leftarrow \text{carbohydrate grams (one serving)} \\ f_a \in \mathbb{R} \leftarrow \text{fats grams (one serving)} \\ f_i \in \mathbb{R} \leftarrow \text{fiber grams (one serving)} \\ s \in \mathbb{R} \leftarrow \text{sugar grams (one serving)} \\ h \in \mathbb{N} \leftarrow \text{historical sales count} \\ g \leftarrow \text{grade level} \\ d \leftarrow \text{day of week} \\ \vdots \end{bmatrix}$$

FeatureMatrix

feature_matrix

time_slot_id	item	item_ids	GramsPerServing_z	Calories_z	Protein_z	Total Carbohydrate_z	Dietary Fiber_z	Total Sugars_z	Added Sugars_z	Total Fat_z	Saturated Fat_z	Trans Fat_z	Cholesterol_z	Sodium_z	Vitamin D (D2 + D3)_z	Calcium_z	Iron_z	Potassium_z	Vitamin A_z	Vitamin C_z
66	CEREAL MEAL	35	-0.8172231	0.018554451	-0.8371911	0.94154704	-0.35495368	0.45390528	1.5907873	-0.32550797	-0.45374262	-0.13631158	-0.8662756	-0.12056391	0.40607285	-0.46420148	3.7388144	-1.1857142	0.5169432	-0.21713334
66	BAGEL W/CREAM CHEESE	20	-0.57274663	0.09144855	-0.37600252	0.38209945	-0.9023242	-0.44208848	-0.57618785	-0.02907724	0.63007486	-0.13631158	0.12370087	0.12556031	-0.6516272	-0.6906834	-0.11078365	-1.1343945	-0.70502406	-0.4355533
66	ALC BREAKFAST ENTREE	7	-0.30717346	-0.7103866	-0.7218939	-0.48815235	-0.35495368	-0.6980867	-0.37919012	-0.9183695	-0.81501514	-0.13631158	-0.8662756	-0.6743434	-0.6516272	-0.7740967	-0.40690657	-0.82134444	-0.6879165	-0.21713334
66	CEREAL/ NO MILK	36	-0.8172231	0.0550015	-0.8371911	0.94154704	-0.35495368	0.45390528	1.5907873	-0.32550797	-0.45374262	-0.13631158	-0.8662756	-0.07441562	0.40607285	-0.46420148	3.7388144	-1.1857142	0.5169432	-0.21713334
66	$1.00 WATER 16.9oz	1	-0.40898144	-0.92906886	-1.0677854	-0.8611174	-0.35495368	-0.5700876	-0.57618785	-1.0665848	-0.81501514	-0.13631158	-0.8662756	-1.0742953	-0.6516272	0.06023657	-0.11078365	-0.80851454	-0.6903605	-0.32634333
66	ALC VEGETABLE/FRUIT	12	-0.15666255	0.09144855	0.66167176	0.009134379	0.7397873	-0.6980867	-0.67468673	-0.32550797	-0.81501514	-0.13631158	-0.8662756	0.011727864	-0.6516272	-0.845611	0.18533927	0.2563689	-0.31399453	0.9113699
66	ALC,JUICE 4OZ $.75	13	-0.22417432	-1.2206453	-1.1830825	-0.9854391	-1.4496946	0.58190435	-0.7731856	-1.0665848	-0.81501514	-0.13631158	-0.8662756	-1.0742953	-0.6516272	-0.97374076	-0.70302945	-0.15932053	-0.70502406	0.87496656
66	CEREAL MEAL	35	-0.8172231	0.018554451	-0.8371911	0.94154704	-0.35495368	0.45390528	1.5907873	-0.32550797	-0.45374262	-0.13631158	-0.8662756	-0.12056391	0.40607285	-0.46420148	3.7388144	-1.1857142	0.5169432	-0.21713334
66	MANDARIN PARFAIT	93	1.762247	0.22265793	-0.37600252	1.5631564	0.1924198	3.525884	2.3787782	-0.7701541	-0.81501514	-0.13631158	-0.7177791	-0.91123796	0.93492293	0.77537936	-0.11078365	1.2973666	3.459889	2.0398731
446	ALC BREAKFAST ENTREE	7	-0.30717346	-0.7103866	-0.7218939	-0.48815235	-0.35495368	-0.6980867	-0.37919012	-0.9183695	-0.81501514	-0.13631158	-0.8662756	-0.6743434	-0.6516272	-0.7740967	-0.40690657	-0.82134444	-0.6879165	-0.21713334
446	TURKEY & CHEESE ON BISCUIT	147	0.55921364	1.2285966	1.5840489	0.13345607	-0.35495368	-0.5700876	-0.37919012	1.7495072	2.0751648	-0.13631158	2.0541549	2.2514584	-0.12277717	0.23902227	0.18533927	1.1749913	-0.70502406	-0.4355533
446	BLUEBERRY BREAD W/ STRING CHEESE	29	-0.7522755	-0.068918474	-0.49129966	0.071295224	-0.35495368	-0.6980867	-0.57618785	0.2673535	0.26880237	-0.13631158	0.12370087	-0.48975024	-0.6516272	0.1198318	-0.40690657	-0.80594856	-0.32621422	-0.21713334
446	CEREAL/ NO MILK	36	-0.8172231	0.0550015	-0.8371911	0.94154704	-0.35495368	0.45390528	1.5907873	-0.32550797	-0.45374262	-0.13631158	-0.8662756	-0.07441562	0.40607285	-0.46420148	3.7388144	-1.1857142	0.5169432	-0.21713334
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446	ALC VEGETABLE/FRUIT	12	-0.15666255	0.09144855	0.66167176	0.009134379	0.7397873	-0.6980867	-0.67468673	-0.32550797	-0.81501514	-0.13631158	-0.8662756	0.011727864	-0.6516272	-0.845611	0.18533927	0.2563689	-0.31399453	0.9113699
446	ALC MILK	11	0.7674596	-0.85617477	-0.14540823	-1.1097608	-1.4496946	0.45390528	-0.7731856	-1.0665848	-0.81501514	-0.13631158	-0.61878145	-0.70519894	0.93492293	0.78729844	-0.70302945	0.91839254	-0.32621422	-0.4355533
446	ALC,JUICE 4OZ $.75	13	-0.22417432	-1.2206453	-1.1830825	-0.9854391	-1.4496946	0.58190435	-0.7731856	-1.0665848	-0.81501514	-0.13631158	-0.8662756	-1.0742953	-0.6516272	-0.97374076	-0.70302945	-0.15932053	-0.70502406	0.87496656
826	CEREAL MEAL	35	-0.8172231	0.018554451	-0.8371911	0.94154704	-0.35495368	0.45390528	1.5907873	-0.32550797	-0.45374262	-0.13631158	-0.8662756	-0.12056391	0.40607285	-0.46420148	3.7388144	-1.1857142	0.5169432	-0.21713334
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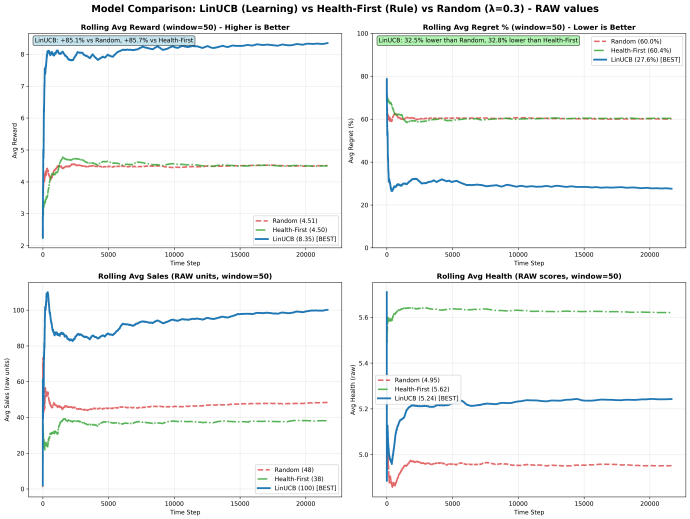
826	ALC VEGETABLE/FRUIT	12	-0.15666255	0.09144855	0.66167176	0.009134379	0.7397873	-0.6980867	-0.67468673	-0.32550797	-0.81501514	-0.13631158	-0.8662756	0.011727864	-0.6516272	-0.845611	0.18533927	0.2563689	-0.31399453	0.9113699
826	ALC MILK	11	0.7674596	-0.85617477	-0.14540823	-1.1097608	-1.4496946	0.45390528	-0.7731856	-1.0665848	-0.81501514	-0.13631158	-0.61878145	-0.70519894	0.93492293	0.78729844	-0.70302945	0.91839254	-0.32621422	-0.4355533
826	ALC,JUICE 4OZ $.75	13	-0.22417432	-1.2206453	-1.1830825	-0.9854391	-1.4496946	0.58190435	-0.7731856	-1.0665848	-0.81501514	-0.13631158	-0.8662756	-1.0742953	-0.6516272	-0.97374076	-0.70302945	-0.15932053	-0.70502406	0.87496656

Results

```
Getting SMART recommendations using trained model...
Date: 2025-10-17, School: HERNDON_HIGH, Meal: lunch

Model loaded from src/tests/results/model_lambda_0.05.joblib
 Loaded trained model: src/tests/results/model_lambda_0.05.joblib
 Using optimal lambda balance found in training

Found 47 typically available items
TOP RECOMMENDATIONS - Using Trained Model (Optimal Balance)
================================================================================
1. SPICY CHICKEN ON BUN SECONDARY
   Sales: 224 (VERY POPULAR )
   Health: 4.3
   Model Score: 167.90 (confidence)

2. CHICKEN ON BUN SECONDARY
   Sales: 42 (Less Popular )
   Health: 4.3
   Model Score: 120.48 (confidence)

3. CHEESE STICKS W/MARINARA SECONDARY
   Sales: 107 (Popular )
   Health: 4.6
   Model Score: 116.21 (confidence)

4. PBJ POWER PACK SECONDARY
   Sales: 94 (Moderate )
   Health: 4.9
   Model Score: 96.15 (confidence)

5. CHICKEN & CHEESE QUESADILLA SECONDARY
   Sales: 68 (Moderate )
   Health: 4.7
   Model Score: 72.17 (confidence)
```

Results


Model Comparison: LinUCB (Learning) vs Health-First (Rule) vs Random (λ=0.3) - RAW values
Rolling Avg Reward (window=50) - Higher is Better
LinUCB: +85.1% vs Random, +85.7% vs Health-First
Avg Reward
Time Step
Random (4.51)
Health-First (4.50)
LinUCB (8.35) [BEST]
Rolling Avg Regret % (window=50) - Lower is Better
LinUCB: 32.5% lower than Random, 32.8% lower than Health-First
Avg Regret (%)
Time Step
Random (60.0%)
Health-First (60.4%)
LinUCB (27.6%) [BEST]
Rolling Avg Sales (RAW units, window=50)
Avg Sales (raw units)
Time Step
Random (48)
Health-First (38)
LinUCB (100) [BEST]
Rolling Avg Health (RAW scores, window=50)
Avg Health (raw)
Time Step
Random (4.95)
Health-First (5.62)
LinUCB (5.24) [BEST]

Conclusion

Summary:

- **Problem:** School meals must balance **popularity vs. nutrition**.
- **Solution:** Applied **Contextual Multi-Armed Bandits (CMAB)** with health-aware rewards.
- **Results:** Achieved results
- **Impact:** Enables **healthier meals** that students actually enjoy.

References

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Thank You / Q&A

Questions or feedback?