ECON 713B - Problem Set 1

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1 All Pay Auction

Consider a symmetric IPV (independent private values) setting with N bidders. Find an equilibrium of the all-pay auction when each bidder's valuation is an iid draw from $F(x) = x^a$ for $a \in (0, \infty)$ and $x \in [0, 1]$.

(a) Define this auction as a Bayesian game.

A Bayesian game is a five-tuple $(I, \{S_i\}, \{u_i(\cdot)\}, \Theta, F(\cdot))$:

- The set of players is $I = \{1, ..., N\}$.
- The action set of player $i \in I$ is $S_i = [0, \infty)$.
- The payoff for player $i \in I$ is

$$u_i(b_1, ..., b_N; v_1, ..., v_N) = u_i(b_1, ..., b_N; v_i) = \begin{cases} v_i - b_i & \text{if } b_i > \max_{j \neq i} b_j \\ \frac{1}{2}(v_i - b_i) + \frac{1}{2}(-b_i) & \text{if } b_i = \max_{j \neq i} b_j \\ -b_i & \text{if } b_i < \max_{j \neq i} b_j \end{cases}$$

- $\Theta = [0, 1] \times ... \times [0, 1]$.
- $F(x) = x^a$ for $a \in (0, \infty)$

(b) Find equilibrium strategies of all players.

Focus on BNE with symmetric, strictly increasing, and differentiable bids $b(v_i)$. Since the F is continuous and $b(v_i)$ is strictly increasing, the probability of a tie is zero. The expected payoff for bidder i is:

$$\begin{aligned} E[u_i(b_1, ..., b_N; v_i)] &= (v_i - b_i) \Pr(b_i > b_j, \forall j \neq i) + (-b_i) \Pr(b_i < b_j, \forall j \neq i) \\ &= v_i \Pr(b_i > b_j, \forall j \neq i) - b_i \end{aligned}$$

Suppose bidder $j \neq i$ submit $b(v_j)$:

$$\begin{aligned} \Pr(b_i > b_j, \forall j \neq i) &= \Pr(b(v_i) > b(v_j), \forall j \neq i) \\ &= \Pr(b^{-1}(b(v_i)) > v_j, \forall j \neq i) \\ &=^{iid} F(b^{-1}(b(v_i)))^{N-1} \\ &= ((b^{-1}(b(v_i)))^a)^{N-1} \\ &= (b^{-1}(b(v_i)))^{aN-a} \end{aligned}$$

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Thus, the expected payoff of bidder i is:

$$E[u_i(b_1,...,b_N;v_i)] = v_i(b^{-1}(b(v_i)))^{aN-a} - b(v_i)$$

FOC $[b(v_i)]$:

$$\begin{aligned}
0 &= (aN-a)v_i(b^{-1}(b(v_i)))^{aN-a-1}\frac{1}{b'(v_i)} - 1\\
\implies b'(v_i) &= (aN-a)v_i^{aN-a}\\
\implies b(v_i) &= \frac{aN-a}{aN-a+1}v_i^{aN-a+1} + c_i
\end{aligned}$$

For $v_i = 0$, bidder i would bid zero: $b(v_i) = 0 \implies c_i = 0$.

$$\implies b(v_i) = \frac{aN-a}{aN-a+1}v_i^{aN-a+1}$$

Since $aN-a+1 > 0$ and $\frac{aN-a}{aN-a+1}$, b is strictly increasing.

(c) Verify that the strategies that you have found do constitute an equilibrium.

We can verify that b is an equilibrium strategy by verifying that $b(v_i)$ is the best response for player i when bidders $j \neq i$ bid $b(v_j)$.

$$\begin{aligned}
E[u_i(b_1,...,b_N;v_i)] &= v_i \Pr\left(b_i > \frac{aN-a}{aN-a+1}v_j^{aN-a+1}, \forall j \neq i\right) - b_i\\
&= v_i \Pr\left(\left(\frac{aN-a+1}{aN-a}b_i\right)^{\frac{1}{aN-a+1}} > v_j, \forall j \neq i\right) - b_i\\
&= v_i\left(\frac{aN-a+1}{aN-a}b_i\right)^{\frac{aN-a}{aN-a+1}} - b_i
\end{aligned}$$

FOC $[b_i]$:

$$\begin{aligned}
0 &= v_i\frac{aN-a}{aN-a+1}\left(\frac{aN-a+1}{aN-a}b_i\right)^{\frac{aN-a}{aN-a+1}-1}\frac{aN-a+1}{aN-a} - 1\\
\implies \frac{1}{v_i} &= \left(\frac{aN-a+1}{aN-a}b_i\right)^{\frac{-1}{aN-a+1}}\\
\implies b_i = b(v_i) &= \frac{aN-a}{aN-a+1}v_i^{aN-a+1}
\end{aligned}$$

Thus, all bidders playing $b(\cdot)$ is an equilibrium.

(d) Does the bidding become more competitive when a increases? Explain.

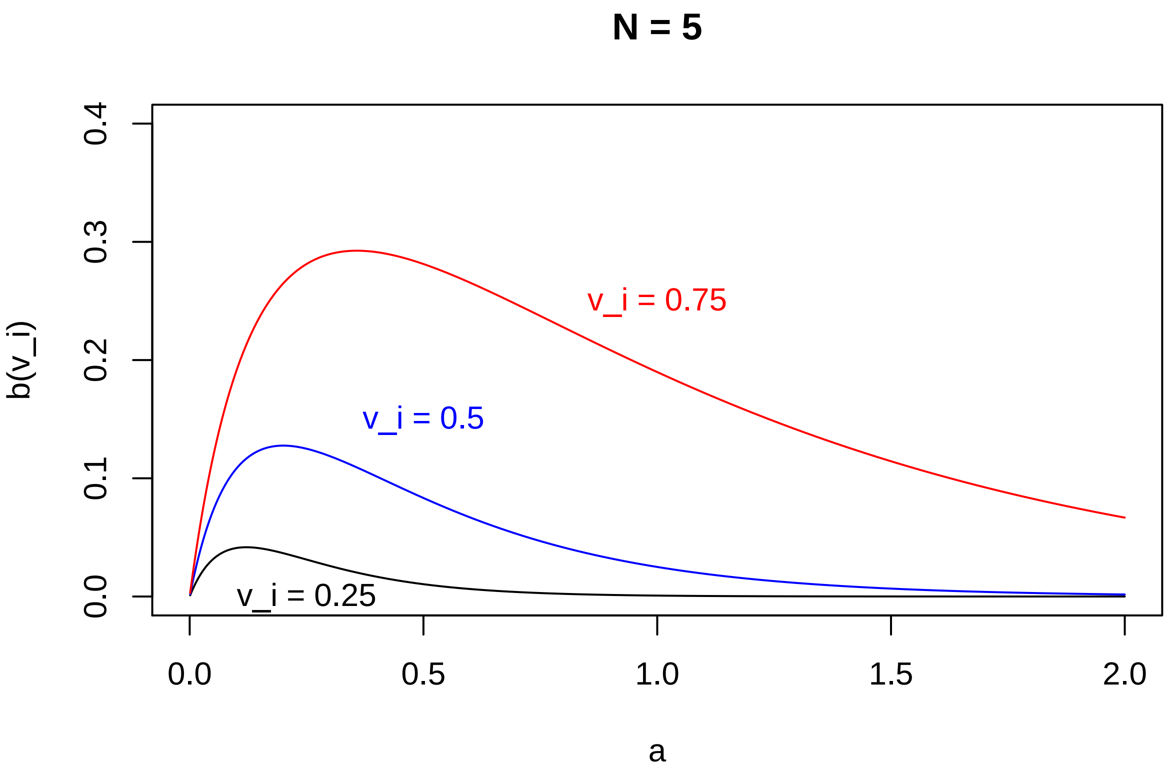
Conditional on v_i and N, a higher a results in more mass closer to 1. Thus, the probability that bidder i wins the auction decreases, so bidder i should decrease her bid. This makes the bidding less competitive. Unconditional on v_i, a higher a results in higher realizations of v_i, so the bids are correspondingly larger.

Consider the derivative of the bidder function with respect to a

$$\begin{aligned}\frac{\partial}{\partial a} b(v_i) &= \frac{\partial}{\partial a}\left(\frac{aN-a}{aN-a+1} v_i^{aN-a+1}\right) \\ &= \frac{N-1}{aN-a+1} v_i^{aN-a+1} - \frac{(aN-a)(N-1)}{(aN-a+1)^2} v_i^{aN-a+1} + \frac{(N-1)(aN-a)}{aN-a+1} v_i^{aN-a+1} \log(v_i)\end{aligned}$$

The derivative is not strictly positive or negative, so increasing a may increase competition and may decrease competition. But for a sufficiently large a, the derivative is negative, so an increase in a decreases a bid conditional on v_i.

We can see that a higher a reduces bids for a sufficiently large a in the figure below ($N = 5, a \in (0,2), v_i \in \{0.25, 0.5, 0.75\}$):



(e) Compute the expected payment from each bidder before and after she learns her value.

The expected payment from bidder i conditional on v_i is their bid:

$$b(v_i) = \frac{aN-a}{aN-a+1} v_i^{aN-a+1}$$

The expected payment from bidder i unconditionally is:

$$\begin{aligned}
b(v_i) &= \int_0^1 \frac{aN-a}{aN-a+1} v_i^{aN-a+1} a v_i^{a-1} dv_i \\
&= a\frac{aN-a}{aN-a+1} \int_0^1 v_i^{aN} dv_i \\
&= a\frac{aN-a}{aN-a+1} \left[\frac{1}{aN+1} v_i^{aN+1} \right]_0^1 \\
&= \frac{a^2N-a^2}{(aN-a+1)(aN+1)}
\end{aligned}$$

The expected payoff of bidder i conditional on v_i is:

$$\begin{aligned}
E[u_i(v_i)] &= v_i^{aN-a+1} - b(v_i) \\
&= v_i^{aN-a+1} - \frac{aN-a}{aN-a+1} v_i^{aN-a+1} \\
&= \frac{v_i^{aN-a+1}}{aN-a+1}
\end{aligned}$$

The unconditional expected payoff of bidder i is:

$$\begin{aligned}
\int_0^1 E[u_i(v_i)] f(v_i) dv_i &= \int_0^1 \frac{v_i^{aN-a+1}}{aN-a+1} a v_t^{a-1} dv_i \\
&= \int_0^1 \frac{a v_i^{aN}}{aN-a+1} dv_i \\
&= \left[\frac{a v_i^{aN+1}}{(aN-a+1)(aN+1)} \right]_0^1 \\
&= \frac{a}{(aN-a+1)(aN+1)}
\end{aligned}$$

2 Tricky Seller

Two people are interested in one object. Their valuations are drawn independently from $F(x) = x$ and $F(x) = x^2$, respectively, with $x \in [0, 1]$. The seller's value (a cost, perhaps) for the object is known, $c \in [0, 1]$.

(a) Describe outcome of the First-Price Auction with a reserve price r.

Consider the auction as Bayesian game $(I, \{S_i\}, \{u_i(\cdot)\}, \Theta, F(\cdot))$:

- The set of players is $I = \{1, 2\}$.
- The action set of player $i \in I$ is $B_i = [0, \infty)$.
- The payoff for player $i \in I$ is

$$u_i(b_1, b_2; x_1, x_2) = u_i(b_1, b_2; x_i) = \begin{cases} x_i - b_i & \text{if } b_i > b_j \text{ and } b_i > r \\ \frac{1}{2}(x_i - b_i) & \text{if } b_i = b_j \geq r \\ 0 & \text{otherwise.} \end{cases}$$

- $\Theta = [0, 1] \times [0, 1]$.
- $F_1(x) = x$ and $F_2(x) = x^2$.

Given reserve price r, suppose bidder 1 and bidder 2 use bidding functions $b_1(x_1)$ and $b_2(x_2)$, respectively. The expected payoff of bidder 1 when bidder 2 plays $b_2(x_2)$:

$$\begin{aligned} E[u_1(b_1, b_2; x_1)] &= (x_1 - b_1) \Pr(b_1 > b_2(x_2)) \\ &= (x_1 - b_1) \Pr(b_2^{-1}(b_1) > x_2) \\ &= (x_1 - b_1) F_2(b_2^{-1}(b_1)) \\ &= (x_1 - b_1)(b_2^{-1}(b_1))^2 \end{aligned}$$

FOC $[b_1]$

$$\frac{2(x_1 - b_1)(b_2^{-1}(b_1))}{b_2'(b_2^{-1}(b_1))} = (b_2^{-1}(b_1))^2 \implies b_1(x_1) = x_1 - \frac{1}{2} b_2^{-1}(b_1(x_1)) b_2'(b_2^{-1}(b_1(x_1)))$$

The expected payoff of bidder 2 when bidder 1 plays $b_1(x_1)$:

$$\begin{aligned} E[u_2(b_1, b_2; x_2)] &= (x_2 - b_2) \Pr(b_2 > b_1(x_1)) \\ &= (x_2 - b_2) \Pr(b_1^{-1}(b_2) > x_1) \\ &= (x_2 - b_2) F_1(b_1^{-1}(b_2)) \\ &= (x_2 - b_2) b_1^{-1}(b_2) \end{aligned}$$

FOC $[b_2]$:

$$\frac{x_2 - b_2}{b_1'(b_1^{-1}(b_2))} - b_1^{-1}(b_2) = 0 \implies b_2(x_2) = x_2 - b_1'(b_1^{-1}(b_2(x_2))) b_1^{-1}(b_2(x_2))$$

Thus, we have two differential equations that define the equilibrium bidding strategies for bidder 1 and 2 with the boundary conditions that $b_1(r) = b_2(r) = r$. Notice that both bidders underbid from their value.

(b) Describe outcome of the Second-Price Auction with a reserve price r.

As discussed in lecture, bidding $b(v) = v$ is a weakly dominate strategy in second price auctions. The logic is similar here:

$$b_1(x) = b_2(x) = x$$

I'm assuming here that if one bid is larger than r and one is smaller, the bidder who submitted the larger bid wins the auction and pays r.

(c) What auction and what r will the seller choose? Which player wins more often?

The seller will choose the auction format that maximizes their revenue.

Given r, the profit from a second price auction is:

$$\begin{aligned}
E[\pi] &= E[Revenue] - c \\
&= E[b_2|b_1 > b_2 > r]P(b_1 > b_2 > r) + E[b_1|b_2 > b_1 > r]P(b_2 > b_1 > r) \\
&+ E[r|b_2 > r > b_1]P(b_2 > r > b_1) + E[r|b_1 > r > b_2]P(b_1 > r > b_2) - c \\
&= E[x_2|x_1 > x_2 > r]P(x_1 > x_2 > r) + E[x_1|x_2 > x_1 > r]P(x_2 > x_1 > r) \\
&+ E[r|x_2 > r > x_1]P(x_2 > r > x_1) + E[r|x_1 > r > x_2]P(x_1 > r > x_2) - c \\
&= \int_r^1 \int_r^{x_1} 2x_2^2 dx_2 dx_1 \int_r^1 \int_r^{x_1} 2x_2 dx_2 dx_1 + \int_r^1 \int_r^{x_2} 2x_1 x_2 dx_1 dx_2 \int_r^1 \int_r^{x_2} 2x_2 dx_1 dx_2 \\
&+ r \int_r^1 \int_0^r 2x_2 dx_1 dx_2 + r \int_r^1 \int_0^r 2x_2 dx_2 dx_1 - c \\
&= \int_r^1 [\frac{2}{3}x_2^3]_{x_2=r}^{x_1} dx_1 \int_r^1 [x_2^2]_{x_2=r}^{x_1} dx_1 + \int_r^1 [x_1^2 x_2]_{x_1=r}^{x_2} dx_2 \int_r^1 [2x_2 x_1]_{x_1=r}^{x_2} dx_2 \\
&+ r \int_r^1 [2x_2 x_1]_{x_1=0}^{r} dx_2 + r \int_r^1 [x_2^2]_{x_2=0}^{r} dx_1 - c \\
&= \int_r^1 \frac{2}{3}x_1^3 - \frac{2}{3}r^3 dx_1 \int_r^1 x_1^2 - r^2 dx_1 + \int_r^1 x_2^3 - r^2 x_2 dx_2 \int_r^1 2x_2^2 - 2x_2 r dx_2 \\
&+ r \int_r^1 2x_2 r dx_2 + r \int_r^1 r^2 dx_1 - c \\
&= [\frac{2}{12}x_1^4 - \frac{2}{3}r^3 x_1]_{x_1=r}^1 [\frac{1}{3}x_1^3 - r^2 x_1]_{x_1=r}^1 + [\frac{1}{4}x_2^4 - \frac{1}{2}r^2 x_2^2]_{x_2=r}^1 [\frac{2}{3}x_2^3 - x_2^2 r]_{x_2=r}^1 \\
&+ r[x_2^2 r]_{x_2=r}^1 + r[r^2 x_1]_{x_1=r}^1 - c \\
&= [\frac{1}{6} - \frac{2}{3}r^3 - \frac{1}{6}r^4 + \frac{2}{3}r^4][\frac{1}{3} - x_1 - \frac{1}{3}r^3 + r^3] + [\frac{1}{4} - \frac{1}{2}r^2 - \frac{1}{4}r^4 + \frac{1}{2}r^4][\frac{2}{3} - r - \frac{2}{3}r^3 + r^3] \\
&+ r[r - r^3] + r[r^2 - r^3] - c
\end{aligned}$$

Bidder 2 is more likely to have higher valuation (F_2 has more mass near 1 than F_1), so they are more likely to submit a higher bid. F_2 first order stochastically dominates F_1: $E[x_1] = 1/2$ and $E[x_2] = 2/3$.

(d) Suppose now that $c = 0$ and there is no reserve price. Suppose that a seller can offer discount of α to one of the bidders in the second-price auction. If a bidder is offered a discount $\alpha \in [0;1]$, then, if she wins, she pays only a fraction α of what she had to pay otherwise. Who should be offered a discount? Compute the optimal discount and expected revenues.

The discount should be offered to bidder 1 because she is less likely to win to auction. With the discount, bidder 1 will bid more aggressive and increase the auction revenue. The payoff for bidder 1 with the discount is now:

$$u_1(b_1, b_2; x_1) = \begin{cases} x_1 - \alpha b_2 & \text{if } b_1 > b_2 \\ \frac{1}{2}(x_1 - \alpha b_2) & \text{if } b_1 = b_2 \\ 0 & \text{if } b_1 < b_2 \end{cases}$$

We found that bidding your value in a second price auction without a discount is weakly dominate strategy by considering the highest bid at which the bidder always has weakly positive surplus, $b_1 = x_1$. Similarly, for the auction with a discount, that bid is $b_1 = \frac{x_1}{\alpha}$.

The expected revenue from the auction is:

$$\begin{aligned}
E[\pi] &= E[b_2|b_1 > b_2]P(b_1 > b_2) + E[b_1|b_2 > b_1]P(b_2 > b_1) \\
&= E\left[\alpha x_2 \middle| \frac{x_1}{\alpha} > x_2\right] P\left(\frac{x_1}{\alpha} > x_2\right) + E\left[\frac{x_1}{\alpha} \middle| x_2 > \frac{x_1}{\alpha}\right] P\left(x_2 > \frac{x_1}{\alpha}\right) \\
&= \int_0^1 \int_0^{x_1/\alpha} 2\alpha x_2^2 dx_2 dx_1 \int_0^1 \int_0^{x_1/\alpha} 2x_2 dx_2 dx_1 + \int_0^1 \int_{x_1/\alpha}^1 2x_2 \frac{x_1}{\alpha} dx_2 dx_1 \int_0^1 \int_{x_1/\alpha}^1 2x_2 dx_2 dx_1 \\
&= 4\alpha \int_0^1 \int_0^{x_1/\alpha} x_2^2 dx_2 dx_1 \int_0^1 \int_0^{x_1/\alpha} x_2 dx_2 dx_1 + \frac{4}{\alpha} \int_0^1 \int_{x_1/\alpha}^1 x_2 x_1 dx_2 dx_1 \int_0^1 \int_{x_1/\alpha}^1 x_2 dx_2 dx_1 \\
&= 4\alpha \int_0^1 \frac{1}{3}[x_2^3]_{x_2=0}^{x_1/\alpha} dx_1 \int_0^1 \frac{1}{2}[x_2^2]_{x_2=0}^{x_1/\alpha} dx_1 + \frac{4}{\alpha} \int_0^1 \frac{1}{2}[x_2 x_1^2]_{x_2=x_1/\alpha}^1 dx_1 \int_0^1 \frac{1}{2}[x_2^2]_{x_1/\alpha}^1 dx_1 \\
&= 4\alpha \int_0^1 \frac{1}{3}(x_1/\alpha)^3 dx_1 \int_0^1 \frac{1}{2}[(x_1/\alpha)^2] dx_1 + \frac{4}{\alpha} \int_0^1 \frac{1}{2}[x_1^2 - (x_1/\alpha)x_1^2] dx_1 \int_0^1 \frac{1}{2}[1 - (x_1/\alpha)^2] dx_1 \\
&= \frac{2}{3\alpha^4} \int_0^1 x_1^3 dx_1 \int_0^1 x_1^2 dx_1 + \frac{1}{\alpha} \int_0^1 [x_1^2 - (x_1^3/\alpha)] dx_1 \int_0^1 [1 - (x_1^2/\alpha^2)] dx_1 \\
&= \frac{2}{3\alpha^4} [\frac{1}{4}x_1^4]_{x_1=0}^1 [\frac{1}{3}x_1^3]_{x_1=0}^1 + \frac{1}{\alpha}[\frac{1}{3}x_1^3 - \frac{1}{4}(x_1^4/\alpha)]_{x_1=0}^1 [x_1 - \frac{1}{3}(x_1^3/\alpha^2)]_{x_1=0}^1 \\
&= \frac{1}{18\alpha^4} + \frac{1}{\alpha}[\frac{1}{3} - \frac{1}{4}(1/\alpha)][1 - \frac{1}{3}(1/\alpha^2)] \\
&= \frac{1}{18\alpha^4} + \frac{\alpha^2}{6}
\end{aligned}$$

FOC $[\alpha]$:

$$\frac{2}{9\alpha^5} = \frac{\alpha}{3} \implies \alpha = (\frac{2}{3})^{1/6}$$

Expected revenue with discount:

$$E[\pi|\alpha = (\frac{2}{3})^{1/6}] = \frac{1}{18((\frac{2}{3})^{1/6}])^4} + \frac{((\frac{2}{3})^{1/6}])^2}{6} \approx 0.208$$

3 Third Price Auction

Consider a third-price auction with three players: an auction in which bidder with the highest value wins, but pays only the third highest bid. Assume that valuation of players are iid from the uniform distribution on [0, 1].

(a) Define the auction as a Bayesian game.

For this part, I consider a third-price auction with only three players. A Bayesian game is a five-tuple $(I, \{S_i\}, \{u_i(\cdot)\}, \Theta, F(\cdot))$:

- The set of players is $I = \{1, 2, 3\}$.
- The action set of player $i \in I$ is $B_i = [0, \infty)$.
- The payoff for player $i \in I$ is

$$u_i(b_1, b_2, b_3; v_1, v_2, v_3) = u_i(b_1, b_2, b_3; v_i) = \begin{cases} v_i - b_k & \text{if } b_i > b_j \geq b_k, \\ \frac{1}{3}(v_i - b_k) & \text{if } b_i = b_j = b_k, \\ \frac{1}{2}(v_i - b_k) & \text{if } b_i = b_j > b_k, \\ 0 & \text{otherwise.} \end{cases}$$

- $\Theta = [0, 1] \times [0, 1] \times [0, 1]$.
- $F(v) = v$.

(b) Prove that a bid of $b_i(v_i) = \frac{n-1}{n-2} v_i$ is a symmetric Bayes Nash equilibrium of the third-price auction.

In this part, I consider a third-price auction with n bidders. I show that bidder i's best response to $b(v_{-i}) = \frac{n-1}{n-2} v_{-i}$ is to play $b(v_i) = \frac{n-1}{n-2} v_i$ below and thus it is a symmetric Bayes Nash equilibrium. The expected payoff of bidder i is

$$\begin{aligned} E[u_i(b_1, ..., b_n; v_i)] &= (v_i - E[b_{(n-2)} | b_i > b_j, j \neq i]) \Pr(b_i > b_j, j \neq i) \\ &= \left(v_i - \frac{n-1}{n-2} E\left[v_{(n-2)} | b_i > \frac{n-1}{n-2} v_j, j \neq i \right] \right) \Pr\left(b_i > \frac{n-1}{n-2} v_j, j \neq i \right) \\ &= \left(v_i - \frac{n-1}{n-2} E\left[v_{(n-2)} \middle| \frac{n-2}{n-1} b_i > v_j, j \neq i \right] \right) \Pr\left(\frac{n-2}{n-1} b_i > v_j, j \neq i \right) \\ &= \left(v_i - \frac{n-1}{n-2} E[w_{(n-2)}] \right) F\left(\frac{n-2}{n-1} b_i \right)^{n-1} \\ &= \left(v_i - \frac{n-1}{n-2} \frac{n-2}{n-1} b_i \frac{n-2}{n} \right) \left(\frac{n-2}{n-1} b_i \right)^{n-1} \\ &= \left(v_i - \frac{n-2}{n} b_i \right) \left(\frac{n-2}{n-1} b_i \right)^{n-1} \\ &= \left(\frac{n-2}{n-1} \right)^{n-1} v_i b_i^{n-1} - \frac{n-2}{n} \left(\frac{n-2}{n-1} \right)^{n-1} b_i^n \end{aligned}$$

where $w_j \sim U(0, \frac{n-2}{n-1} b_i)$ for $j \neq i$. Generally, note that if $X_1, ..., X_n \sim U(0, 1)$, then the kth order statistic $X_{(k)} \sim Beta(k, n-k+1) \implies E[X_{(k)}] = \frac{k}{n+1}$. So, $E[w_{(n-2)}] = \frac{n-2}{n-1} b_i \frac{n-2}{n}$.

FOC $[b_i]$:

$$(n-1)\left(\frac{n-2}{n-1}\right)^{n-1} v_i b_i^{n-2} = n\frac{n-2}{n}\left(\frac{n-2}{n-1}\right)^{n-1} b_i^{n-1} \implies b_i(v_i) = \frac{n-1}{n-2}v_i$$

Thus, $b_i(v_i) = \frac{n-1}{n-2}v_i$ is a best response.

(c) Show that the expected revenue of a seller in the third-price auction is $R_3 = \frac{n-1}{n+1}$.

The expected seller revenue is the expected value of the third highest bid:

$$\begin{aligned} R_3 &= E[b(v_{(n-2)})] \\ &= E\left[\frac{n-1}{n-2}v_{(n-2)}\right] \\ &= \frac{n-1}{n-2}E[v_{(n-2)}] \\ &= \frac{n-1}{n-2}\frac{n-2}{n+1} \\ &= \frac{n-1}{n+1} \end{aligned}$$

(d) What is the symmetric Bayes-Nash equilibrium strategy in a kth price auction? (You need only state how each bidder bids; you need not provide a detailed analysis.)

From lecture notes and this problem, we know the bidding function in symmetric BNEs for $k \in \{1, 2, 3\}$:

$$b(v_i) = \begin{cases} \frac{n-1}{n}v_i & k = 1 \\ v_i & k = 2 \\ \frac{n-1}{n-2}v_i & k = 3 \end{cases}$$

These findings suggest that $b(v_i) = \frac{n-1}{n-k+1}$ for all $k \in \mathbb{N}$ is a candidate.